

(10) **Patent No.:** US 9,134,109 B2  
(45) **Date of Patent:** \*Sep. 15, 2015

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LLP

PCT Pub. Date: **Nov. 3, 2011**

US 2013/0094027 A1      Apr. 18, 2013

(57) **ABSTRACT**

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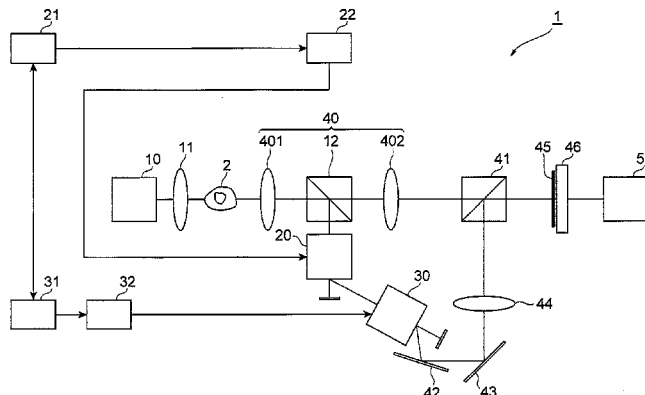
Provided is an observation device which can obtain a phase image of a moving object rapidly with high sensitivity even when using a photodetector having a slow read-out speed per pixel. The observation device **1** comprises a light source **10**, a first modulator **20**, a second modulator **30**, a lens **40**, a beam splitter **41**, a photodetector **46**, and an arithmetic unit **50**. The lens **40** receives scattered light generated by a moving object **2** and forms a Fourier transform image of the object **2**. The photodetector **46** outputs data representing a sum in a v direction of data temporally changing at a frequency corresponding to a Doppler shift frequency of the light having reached each position on a light-receiving surface through the lens **40** at each position in a u direction at each time. The arithmetic unit **50** obtains an image of the object **2** according to the output of the photodetector **46**.

(57) **ABSTRACT**

(57) **ABSTRACT**

**28 Claims, 63 Drawing Sheets**

See application file for complete search history.



(51) **Int. Cl.****G02B 21/14** (2006.01)**G02B 27/52** (2006.01)**G03H 1/04** (2006.01)**G03H 1/08** (2006.01)(52) **U.S. Cl.**

CPC ..... **G02B 27/52** (2013.01); **G03H 1/0443**  
 (2013.01); **G03H 1/0866** (2013.01); **G03H**  
**2001/045** (2013.01); **G03H 2001/0447**  
 (2013.01); **G03H 2001/0463** (2013.01); **G03H**  
**2210/62** (2013.01)

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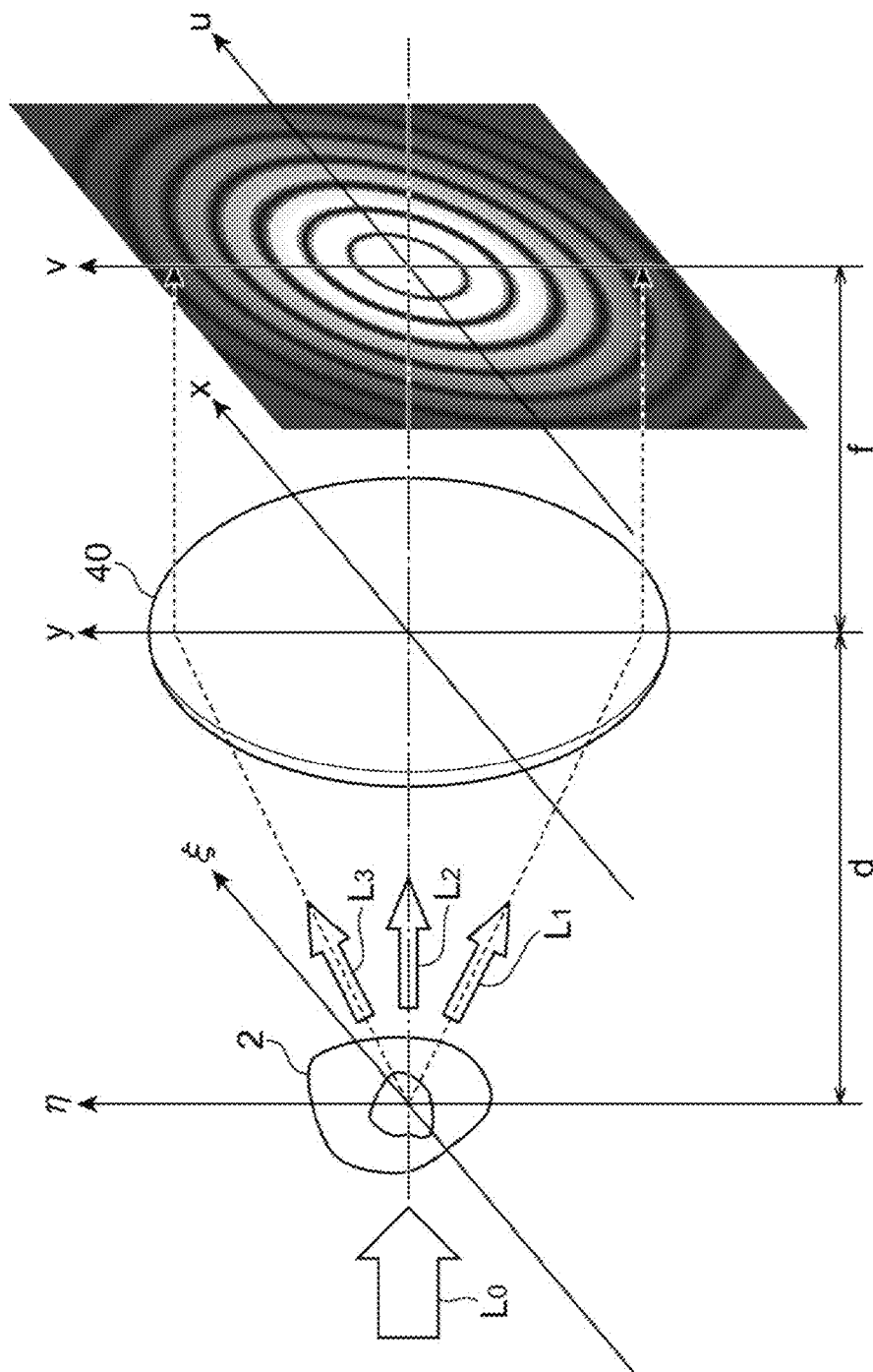
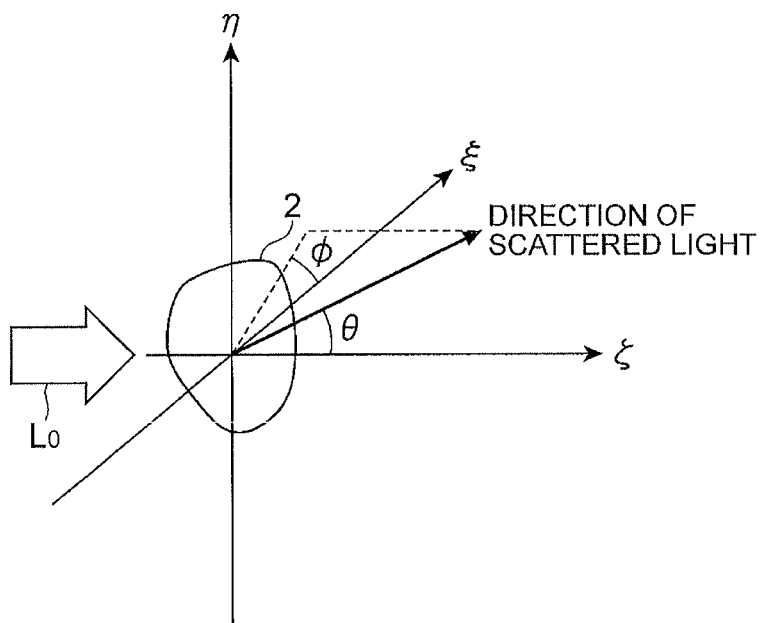
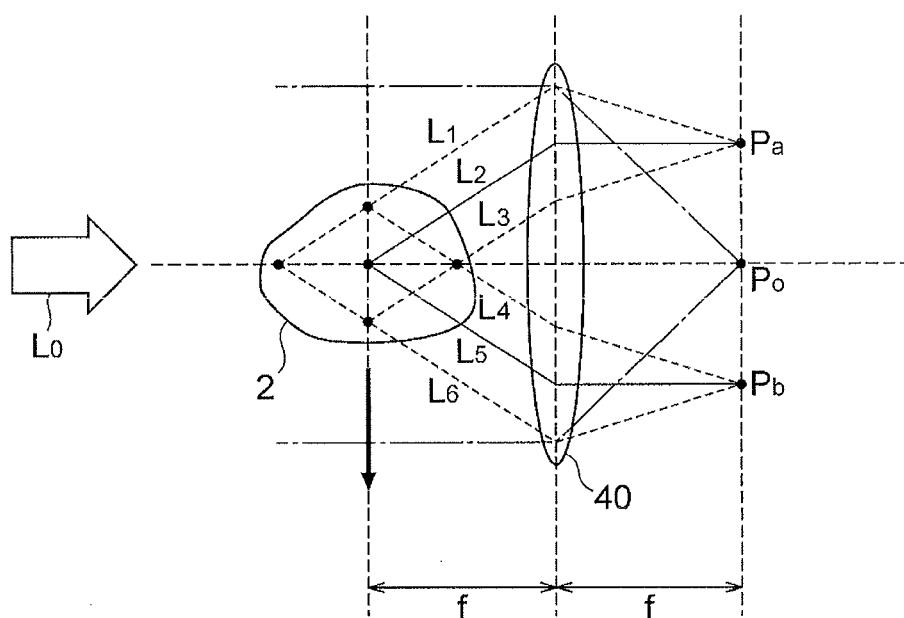
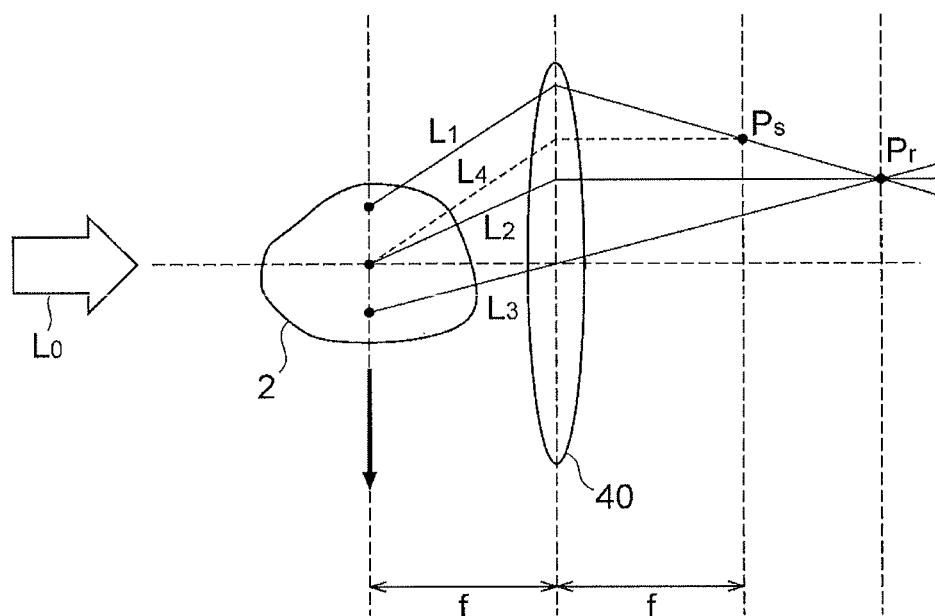


Fig. 1

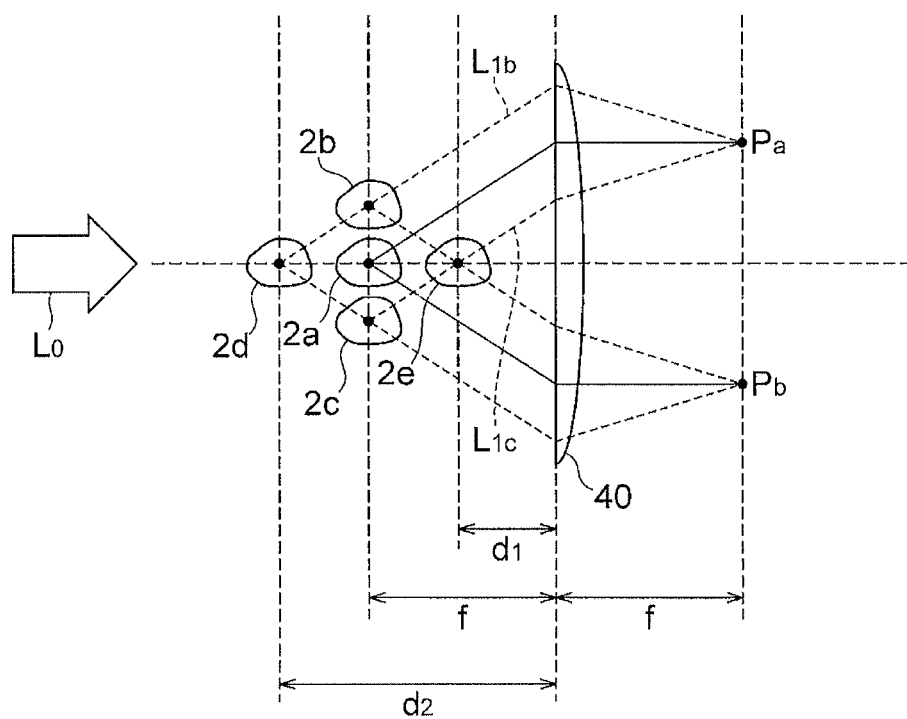
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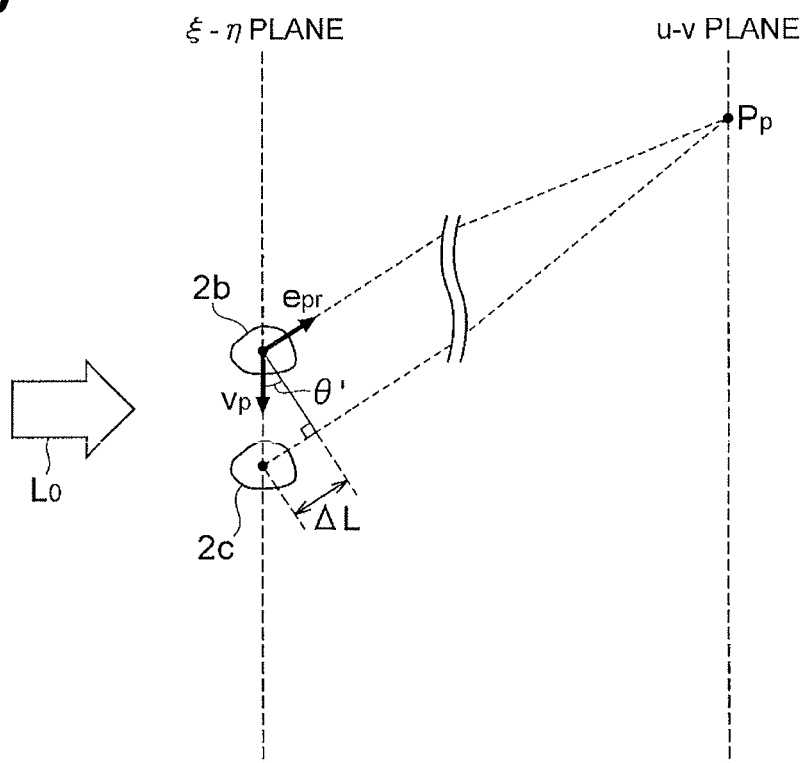
**Fig.3**



**Fig.4**

**Fig.5**



**Fig. 6**



**Fig.7**

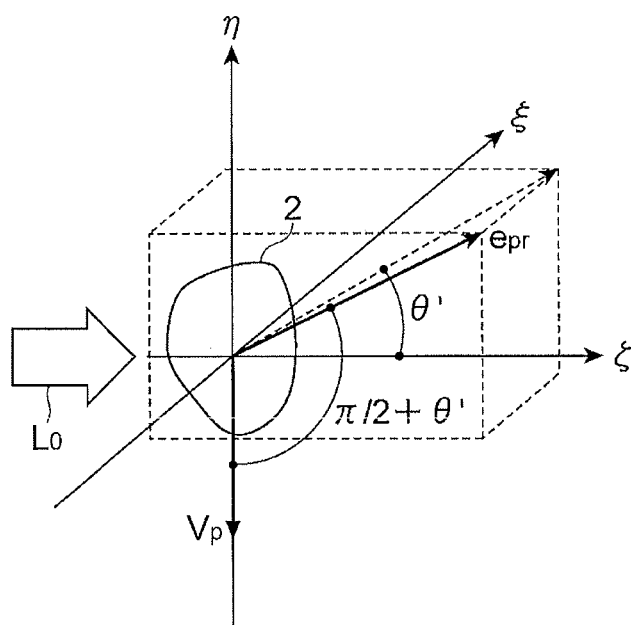
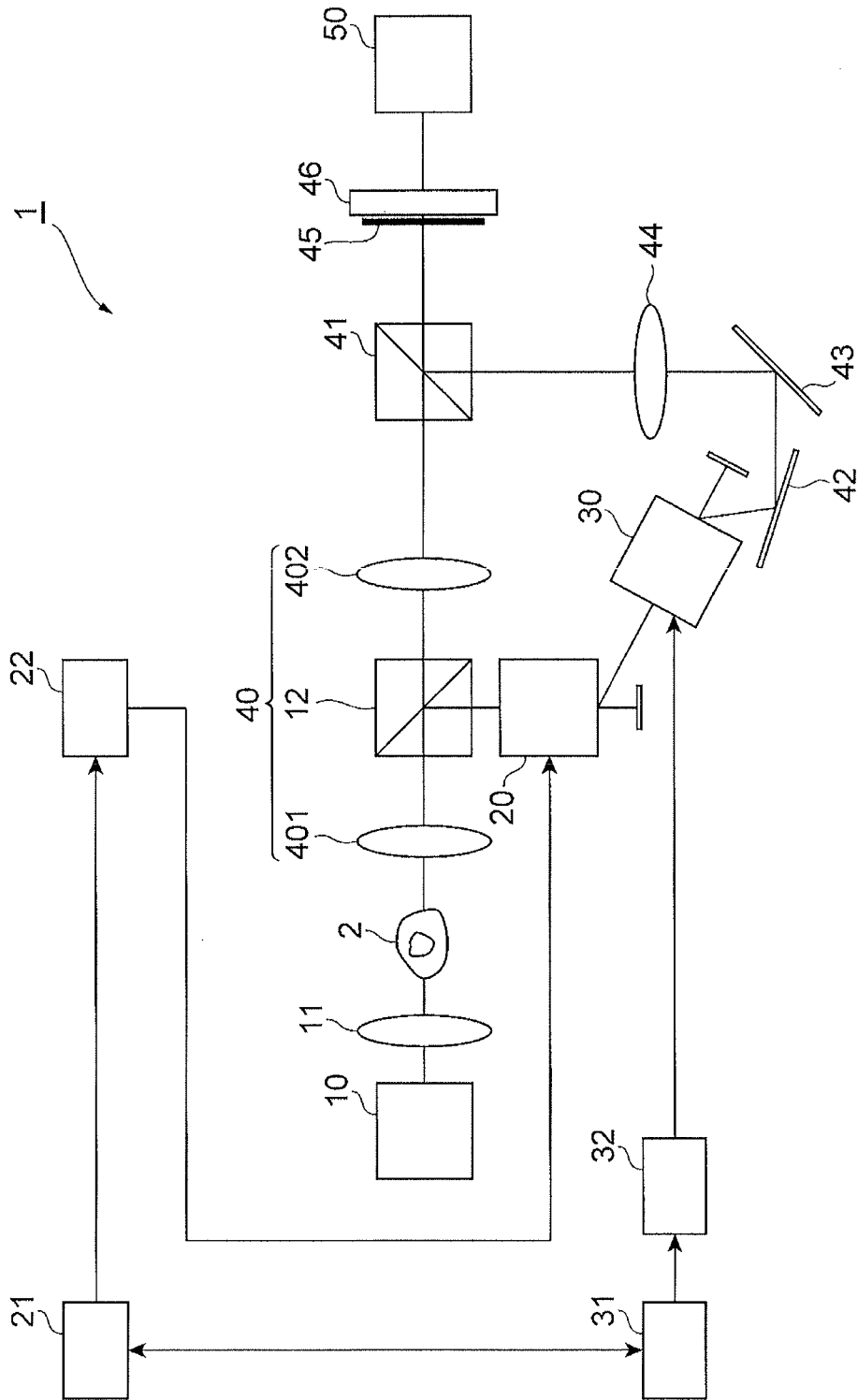
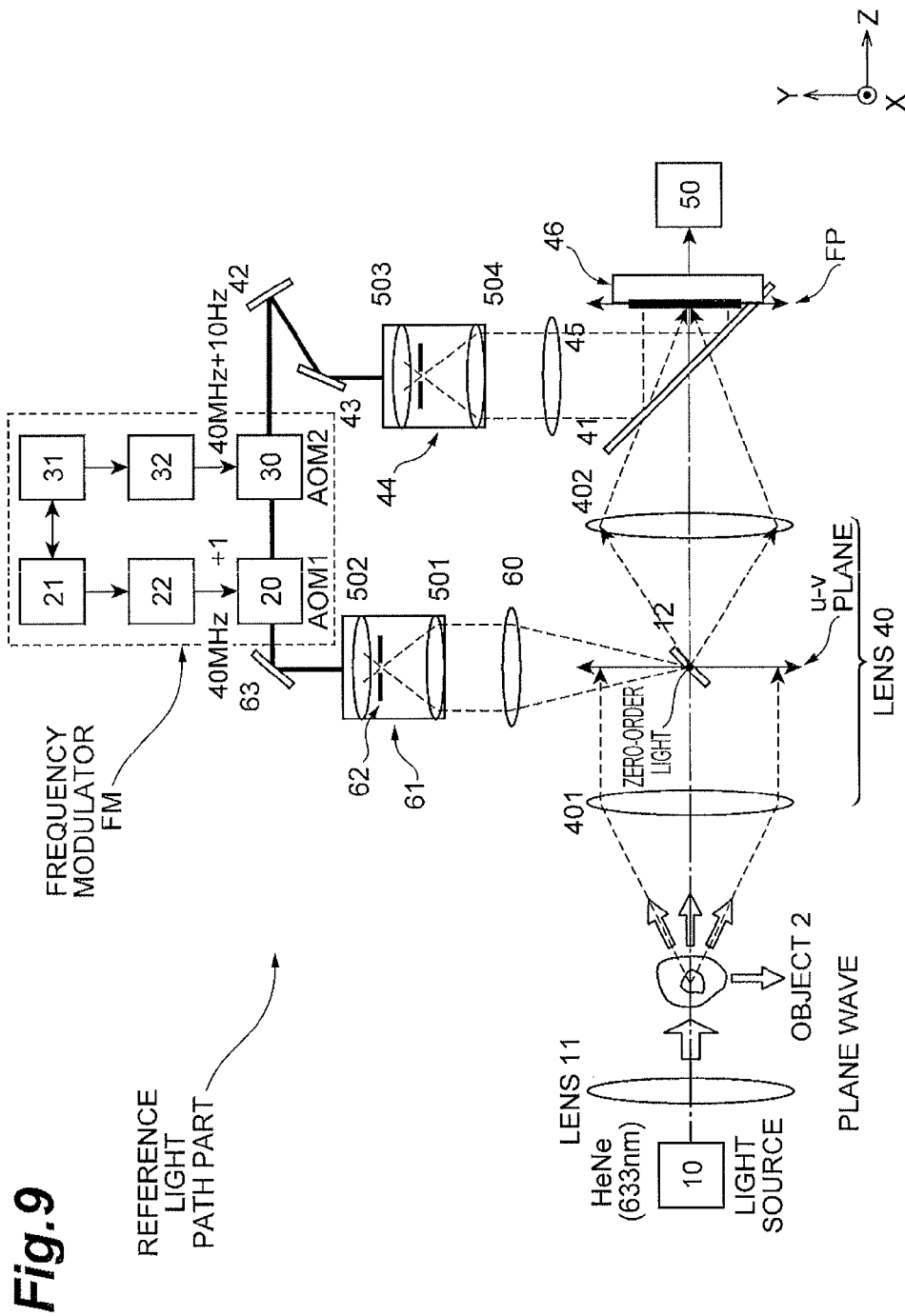
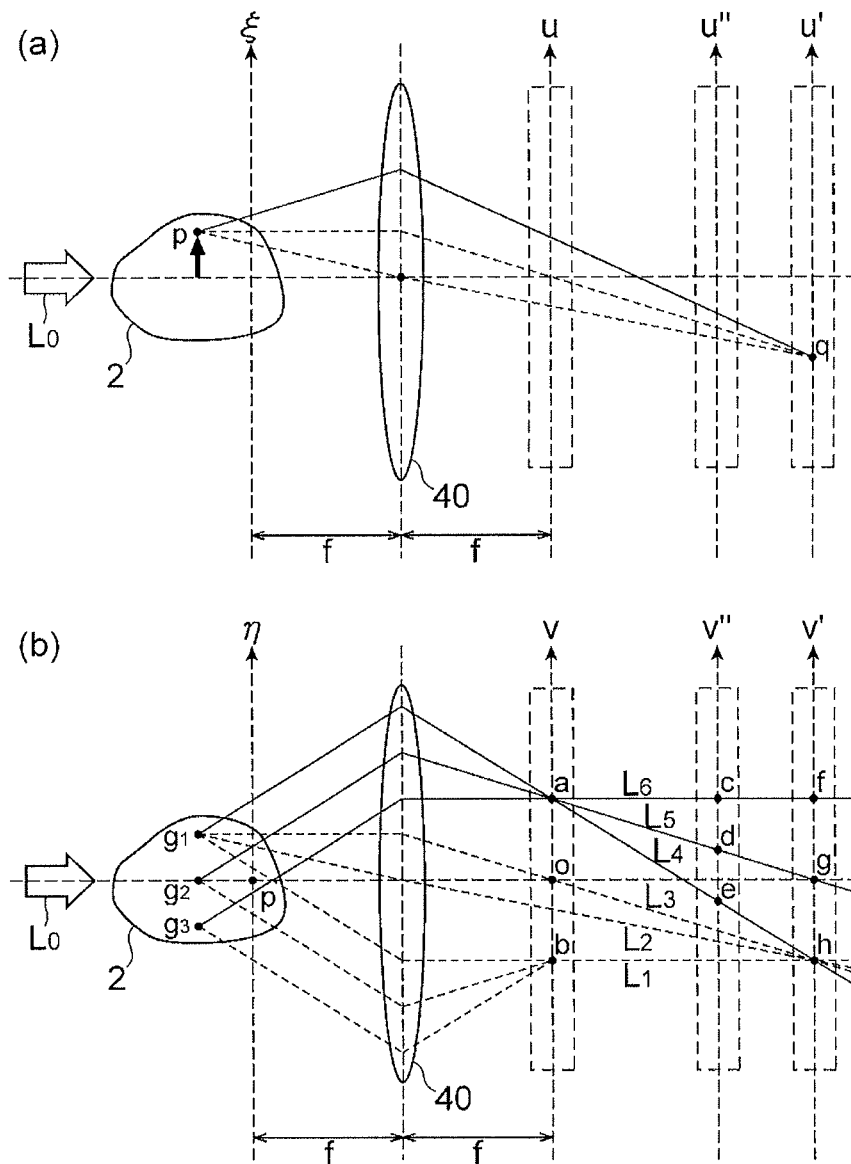


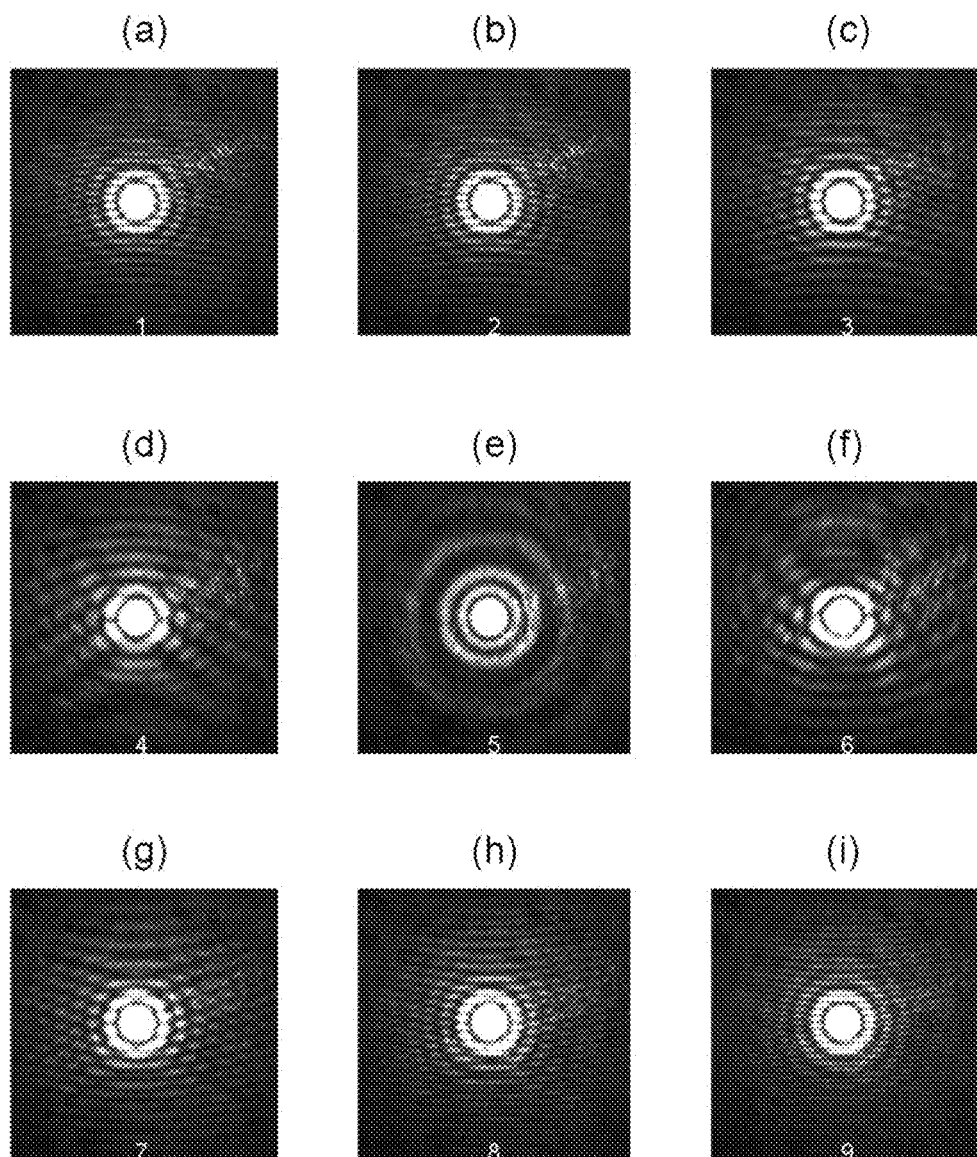
Fig. 8

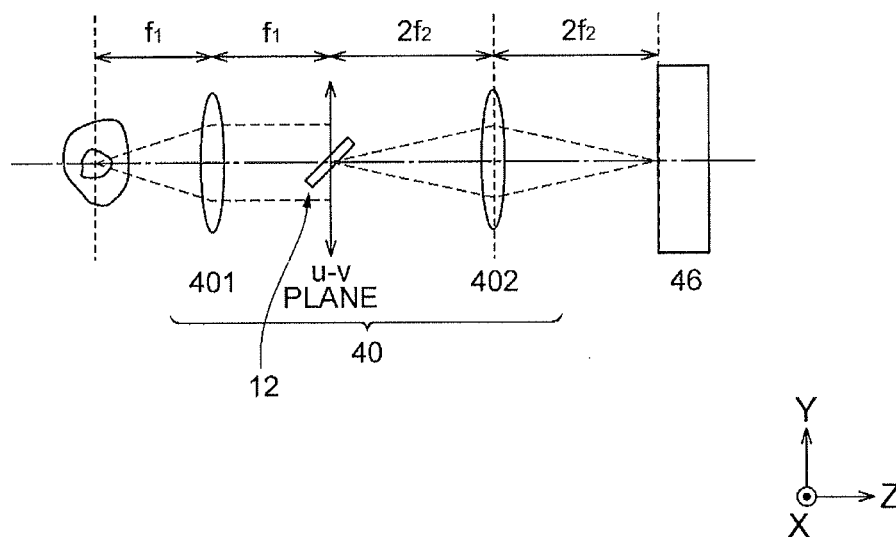


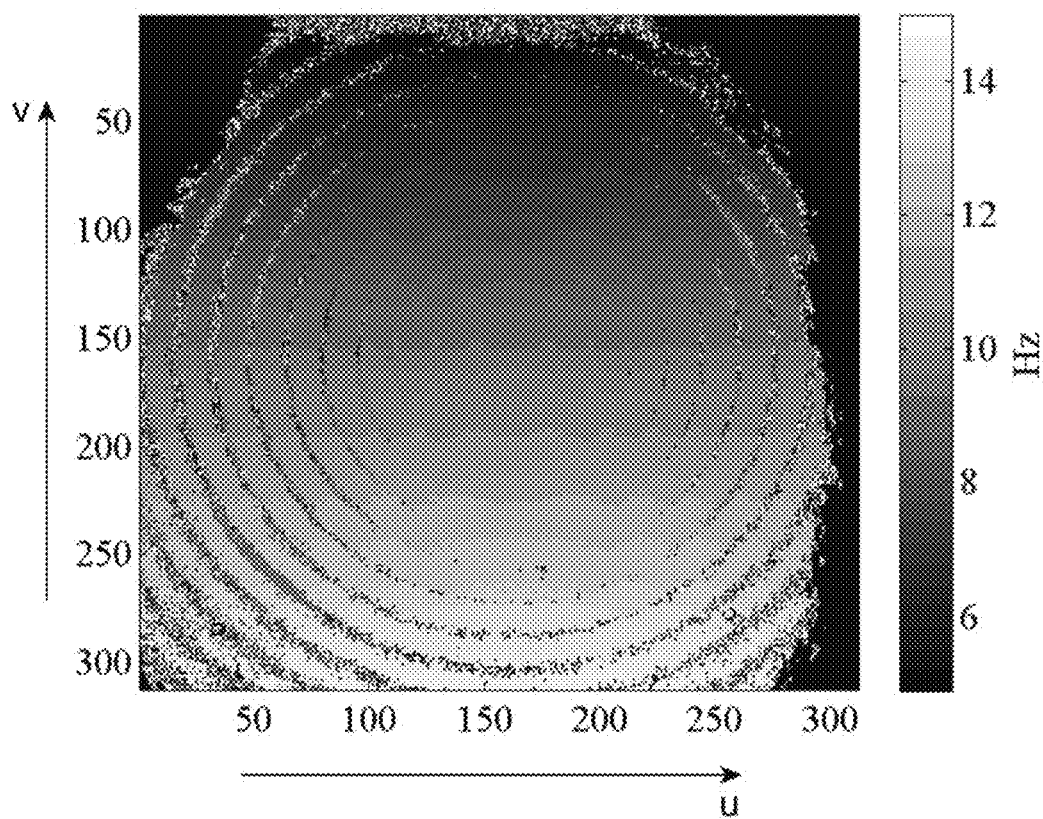


**Fig.10**



**Fig.11**

**Fig. 12**

**Fig. 13**

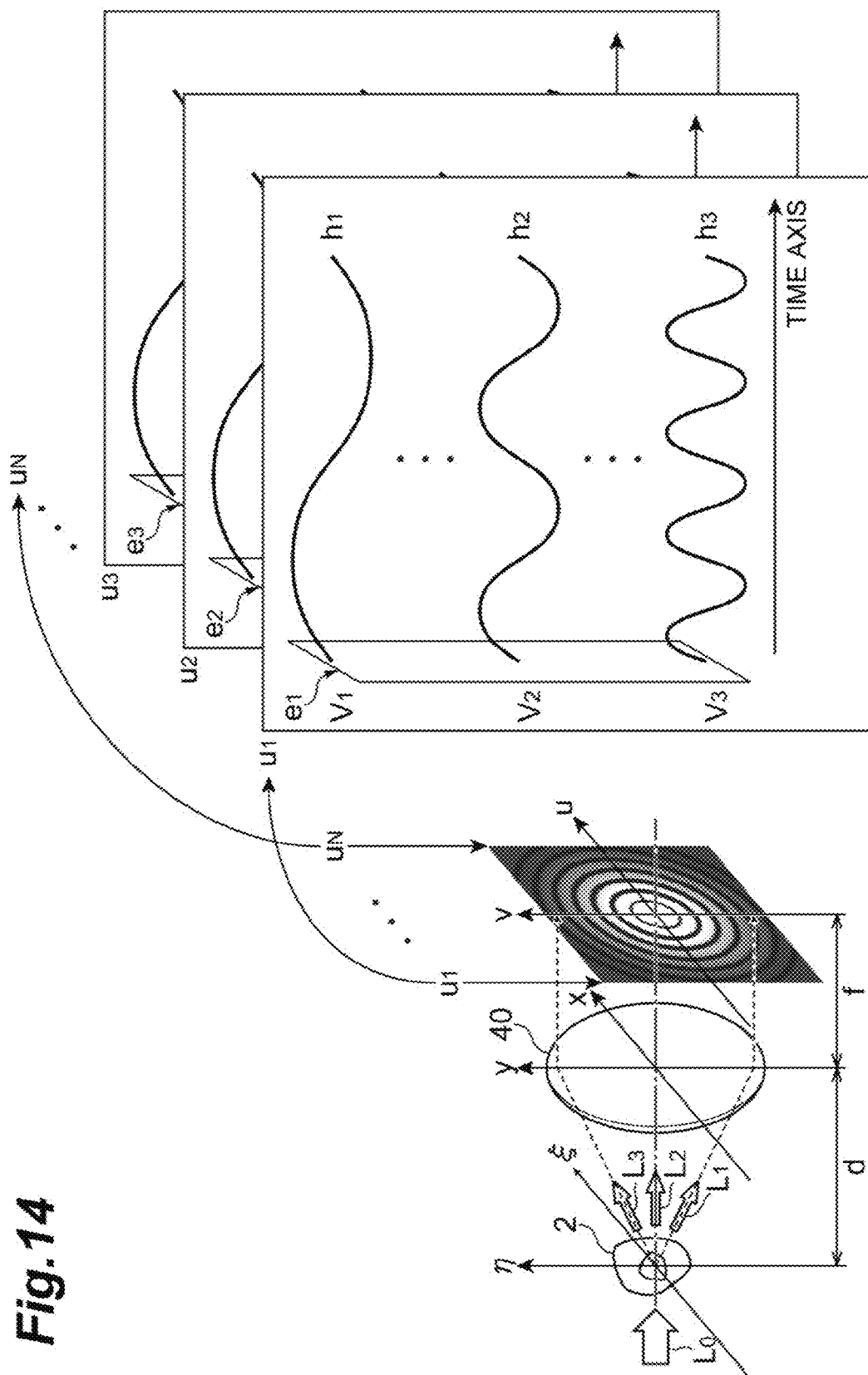
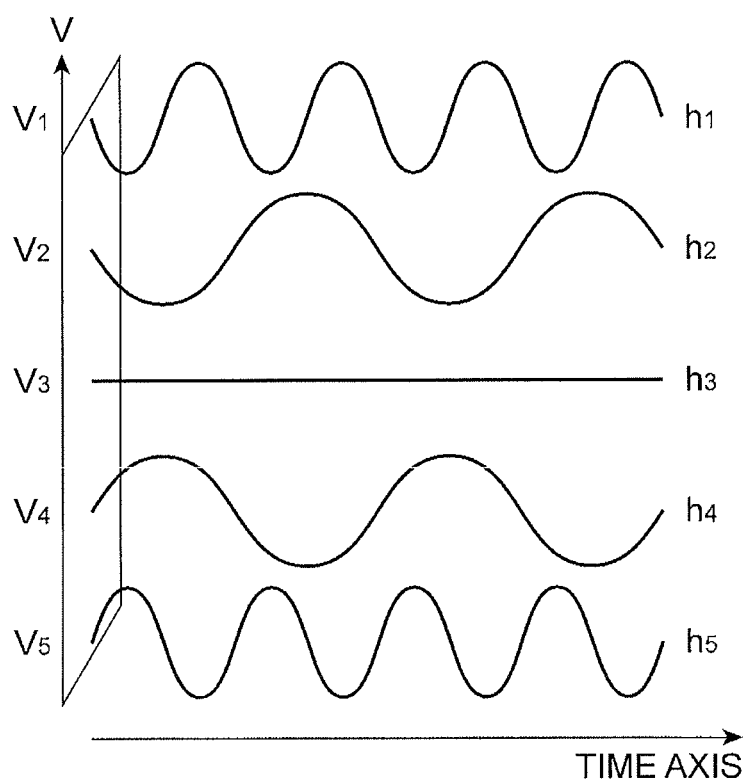
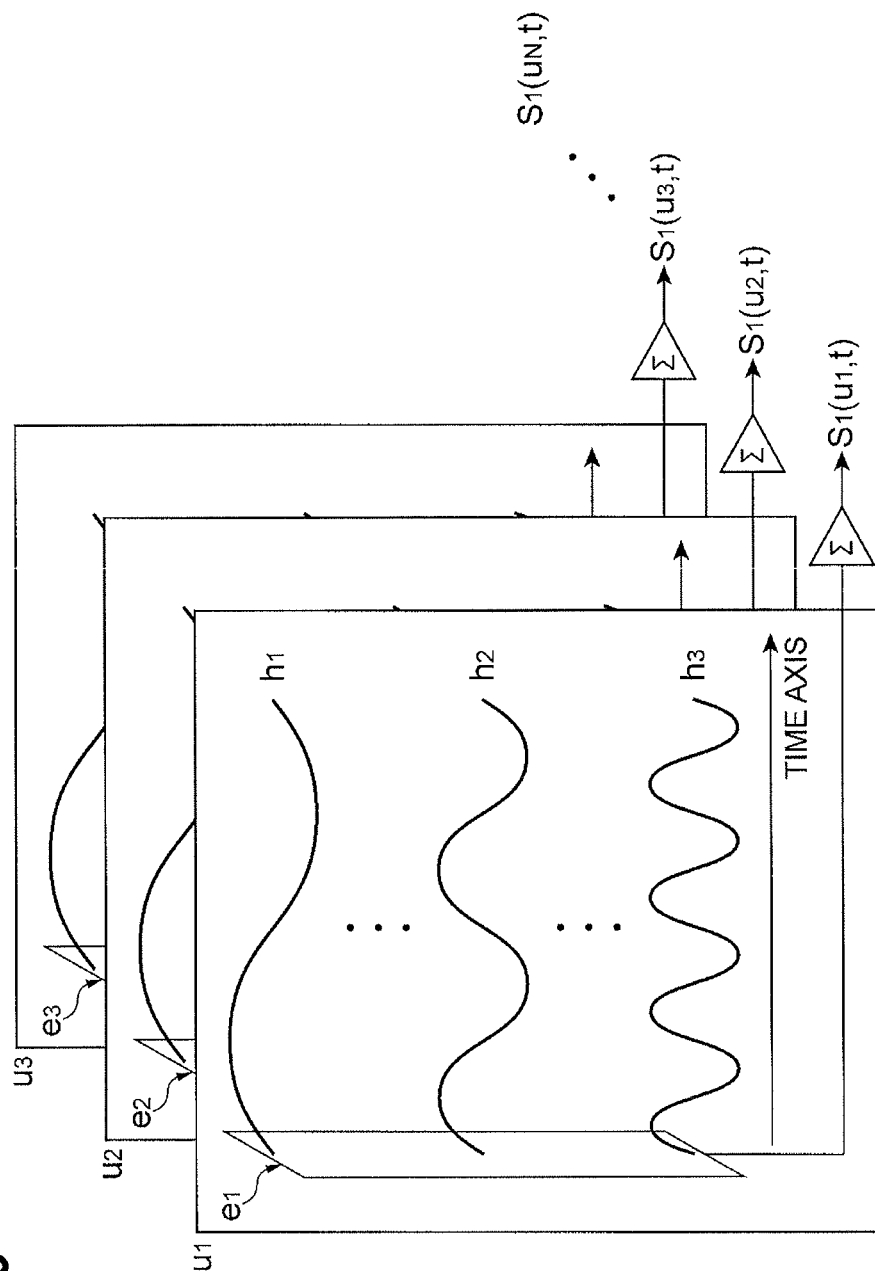


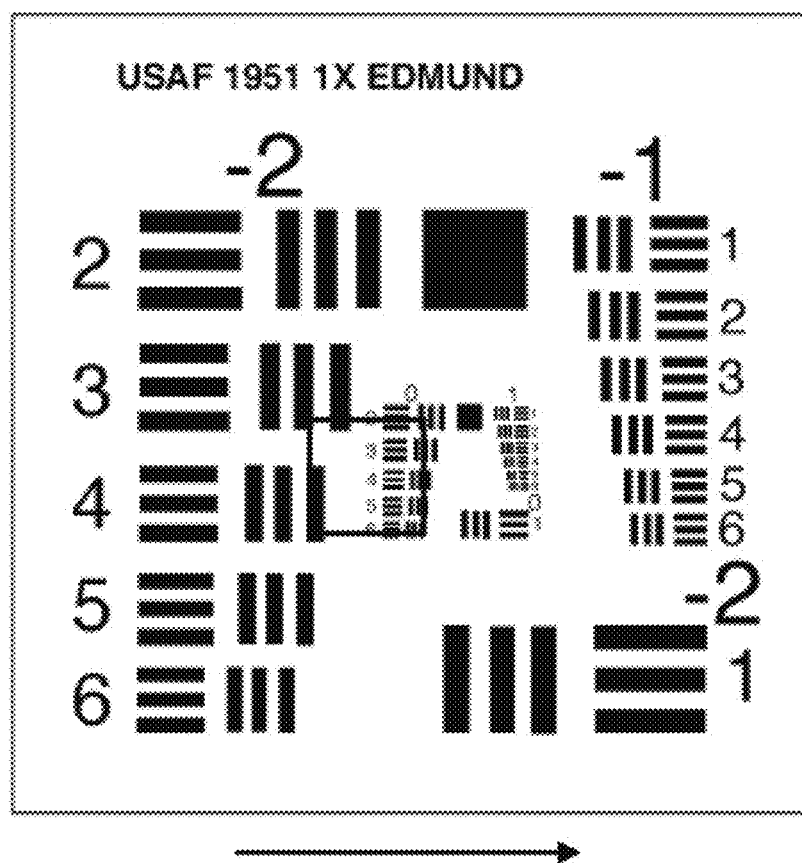
Fig. 14

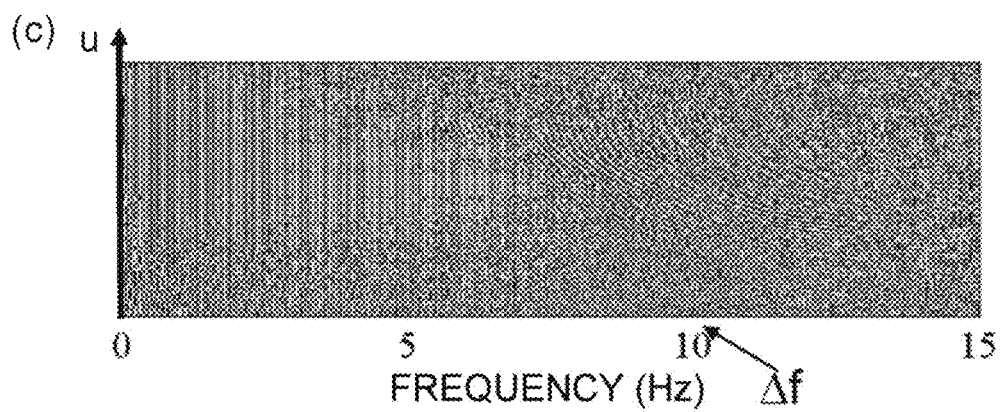
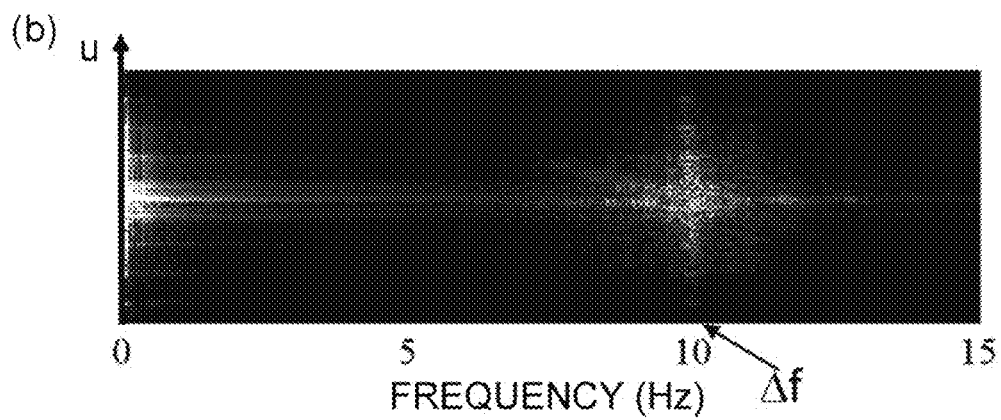
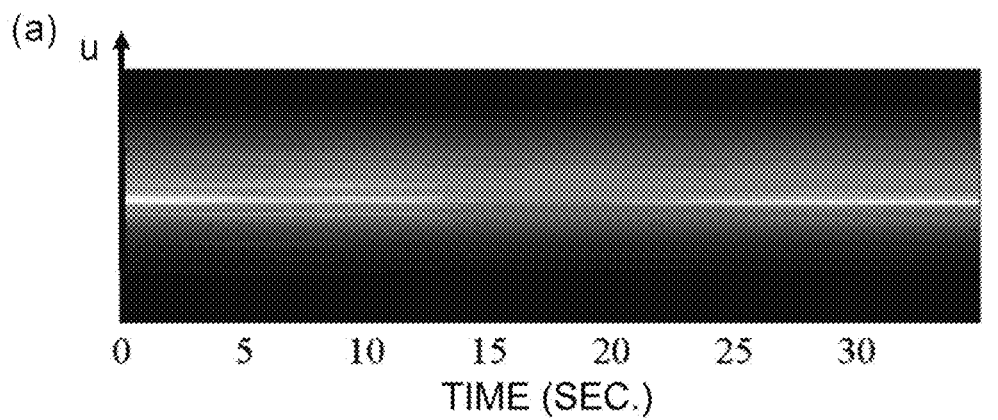


**Fig.15**

**Fig.16**

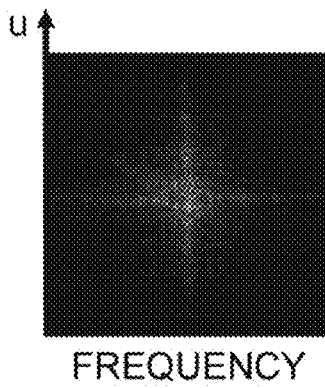


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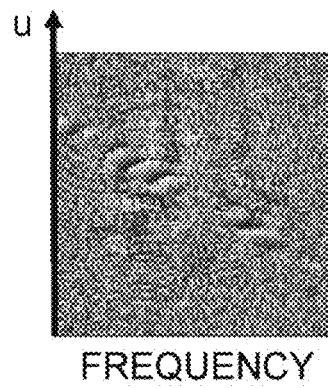
**Fig.18**

**Fig. 19**

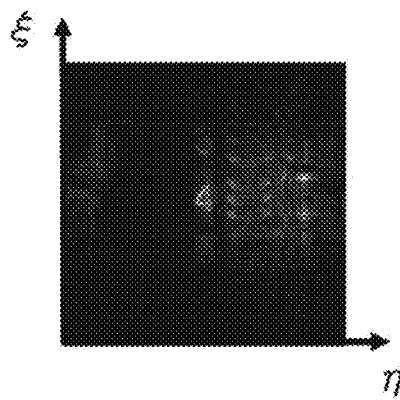
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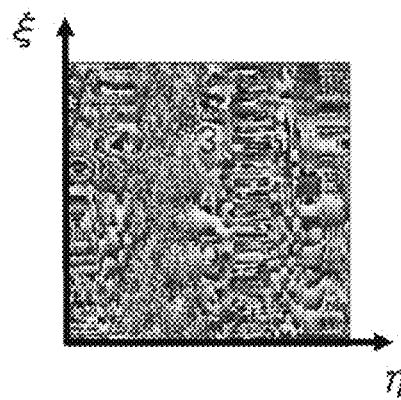
(b)



(c)



(d)



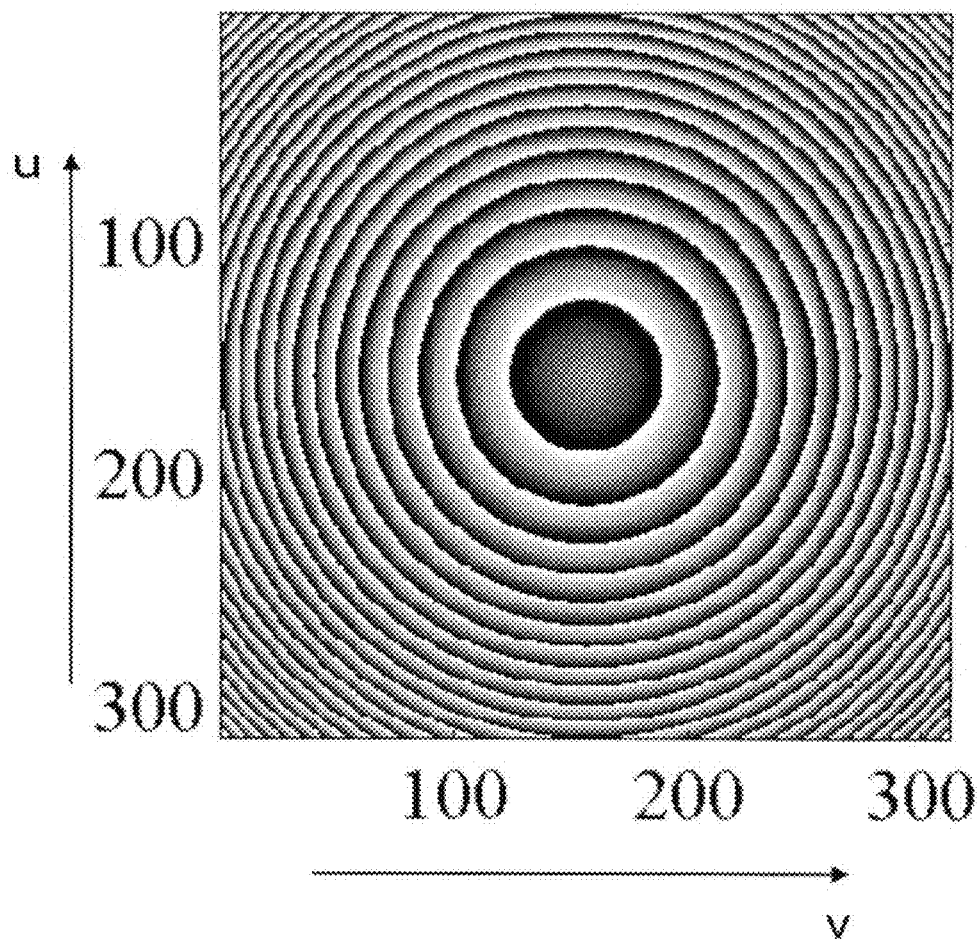
***Fig. 20***

Fig. 21

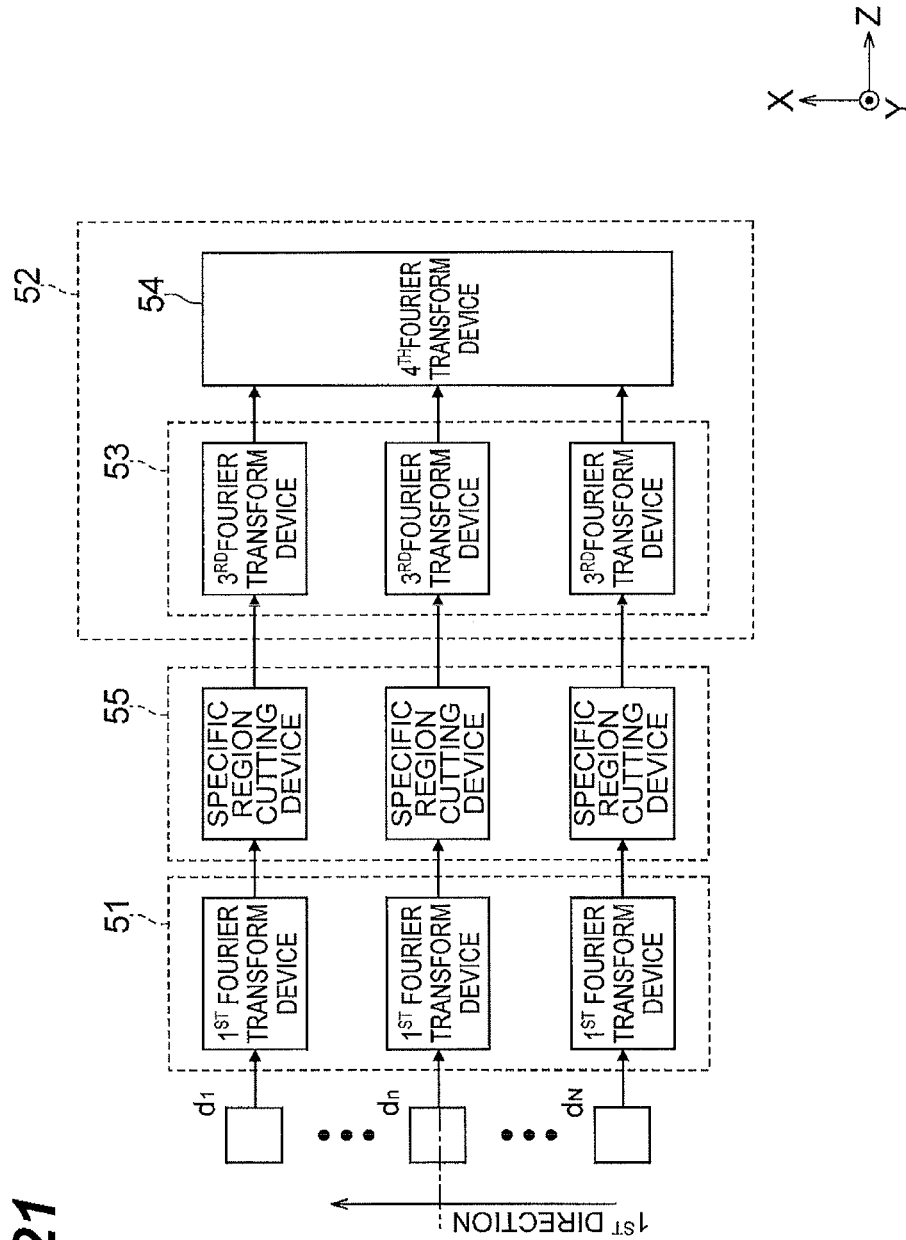
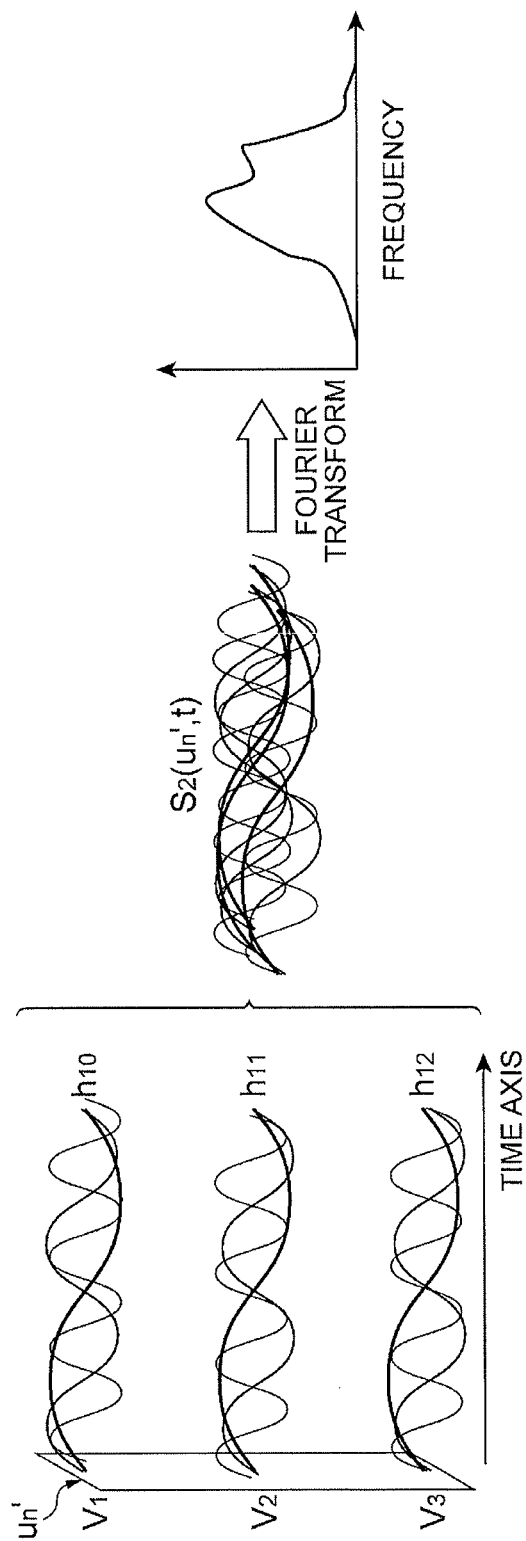
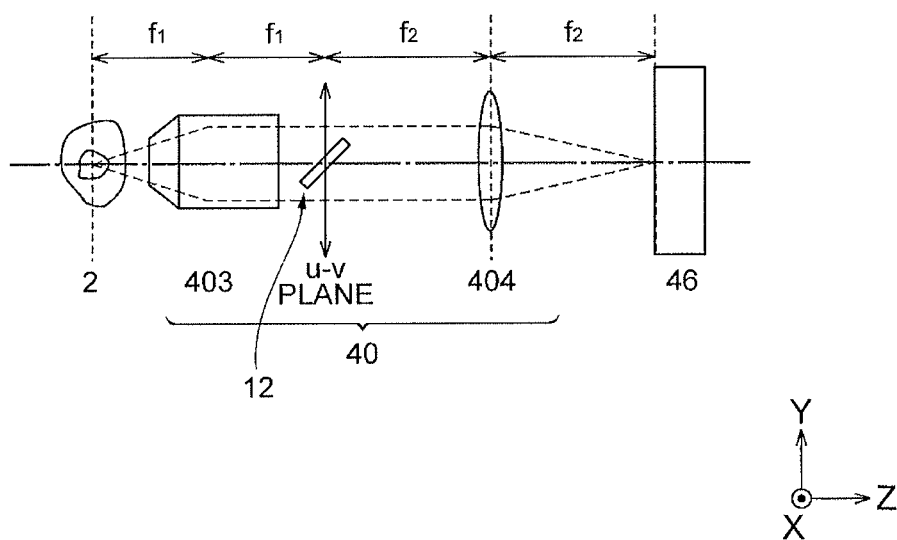
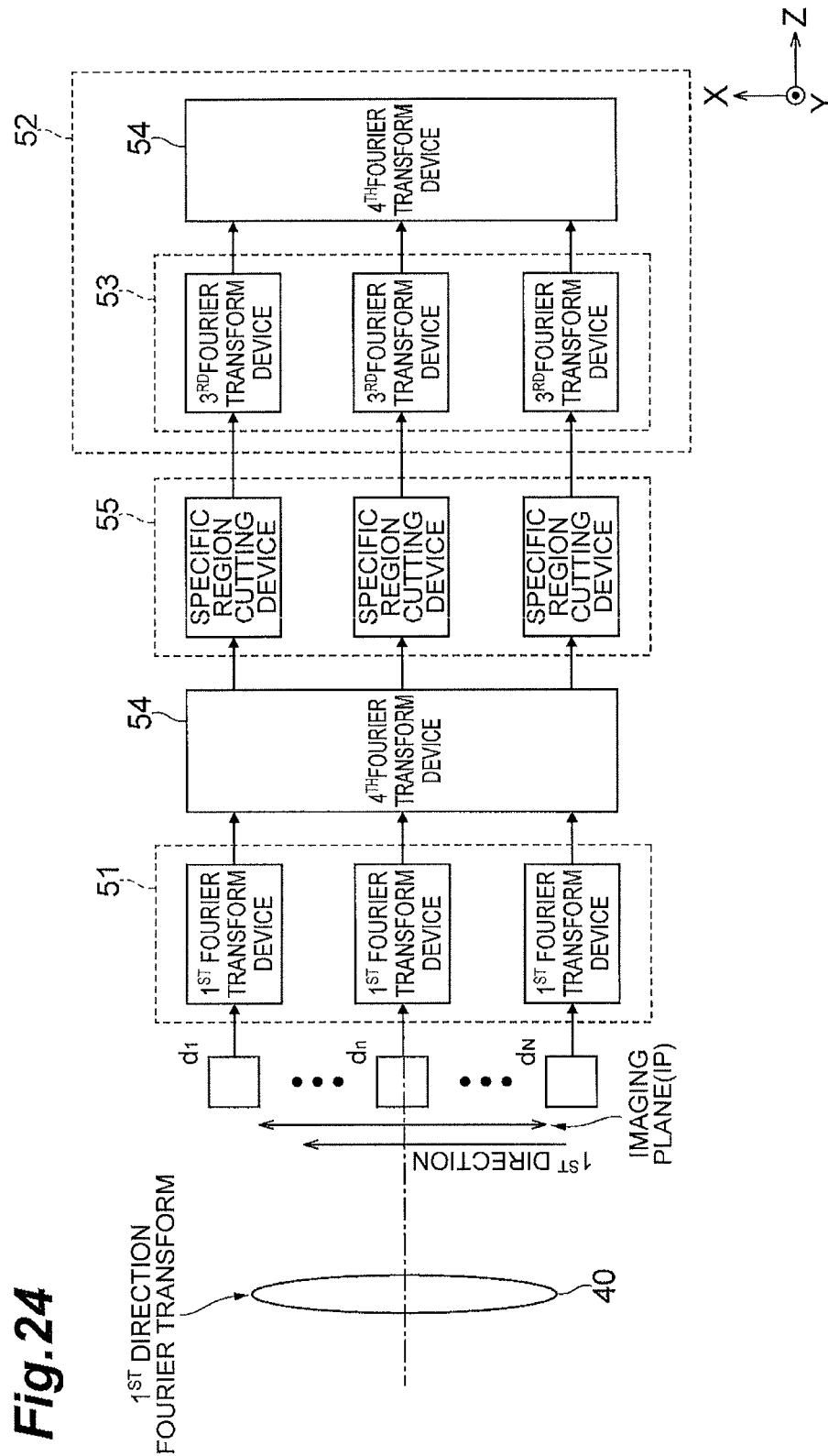


Fig. 22

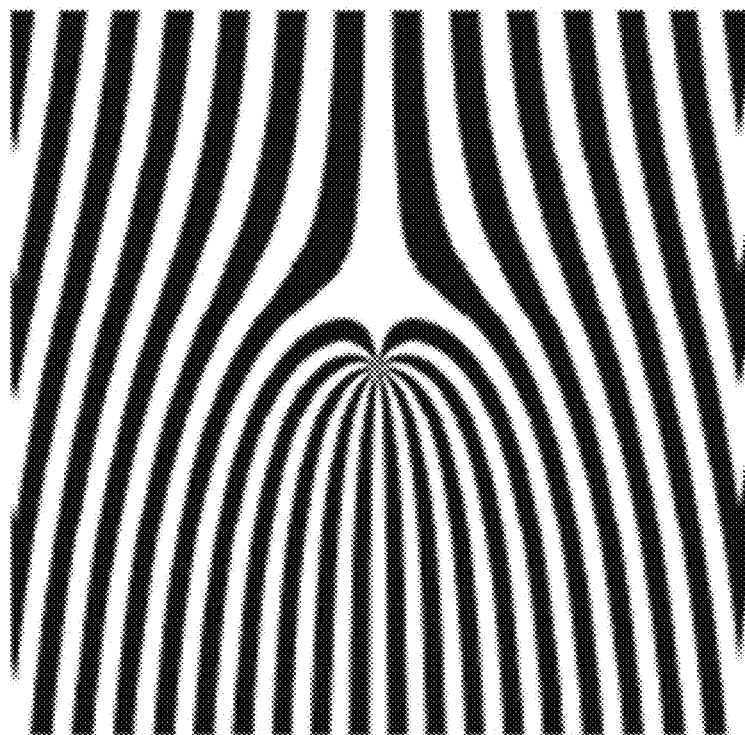


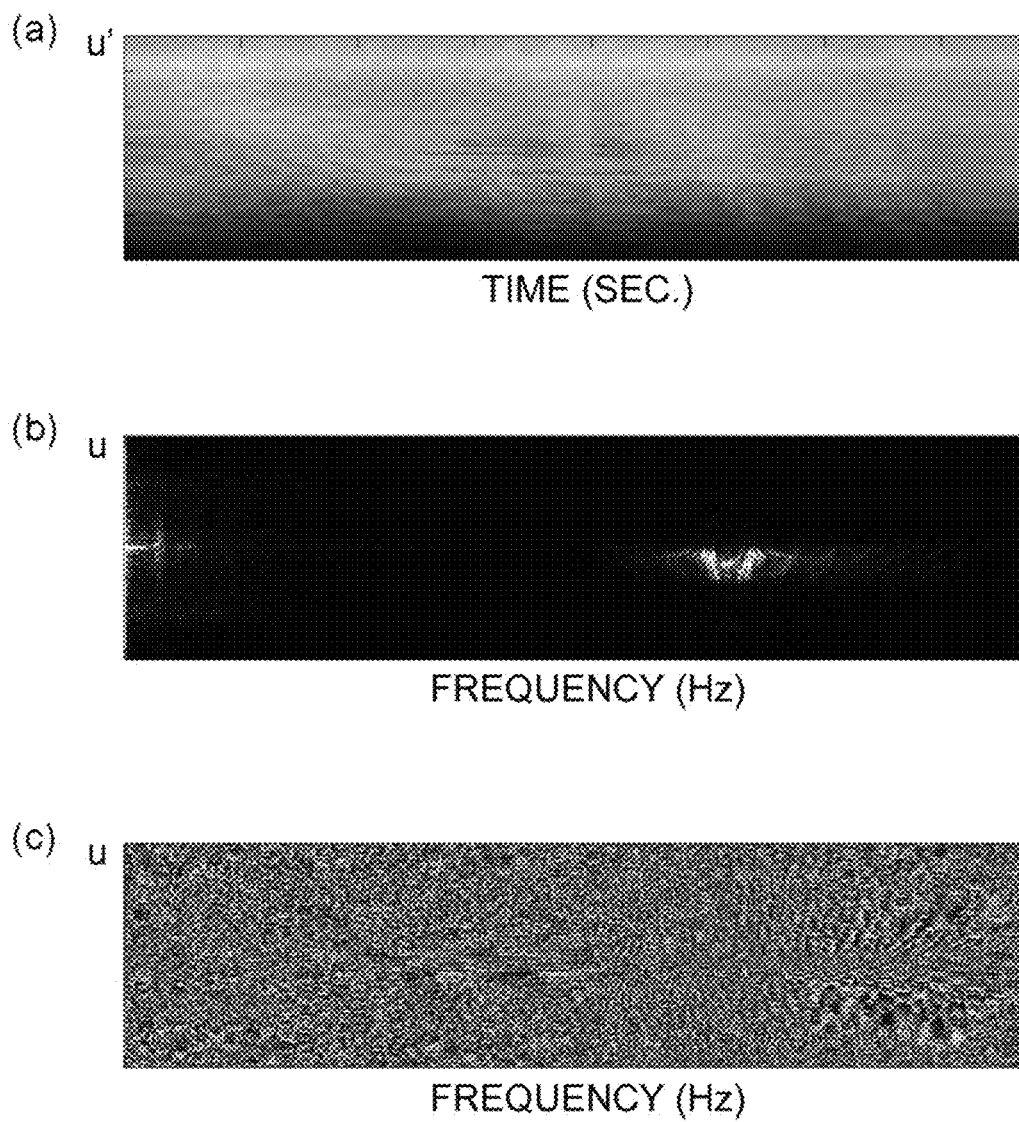


**Fig. 23**



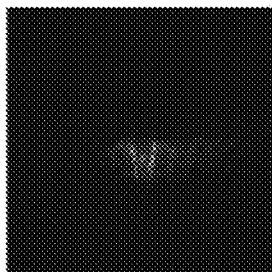
***Fig.25***



**Fig.26**

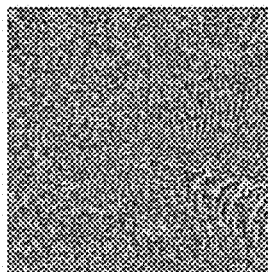
**Fig.27**

(a)

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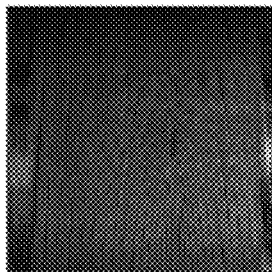
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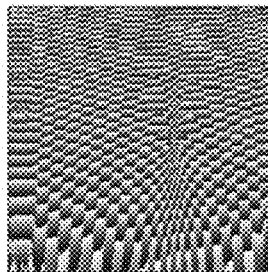
 $u'$ 

FREQUENCY

(c)

 $\xi$  $\eta$ 

(d)

 $\xi$  $\eta$

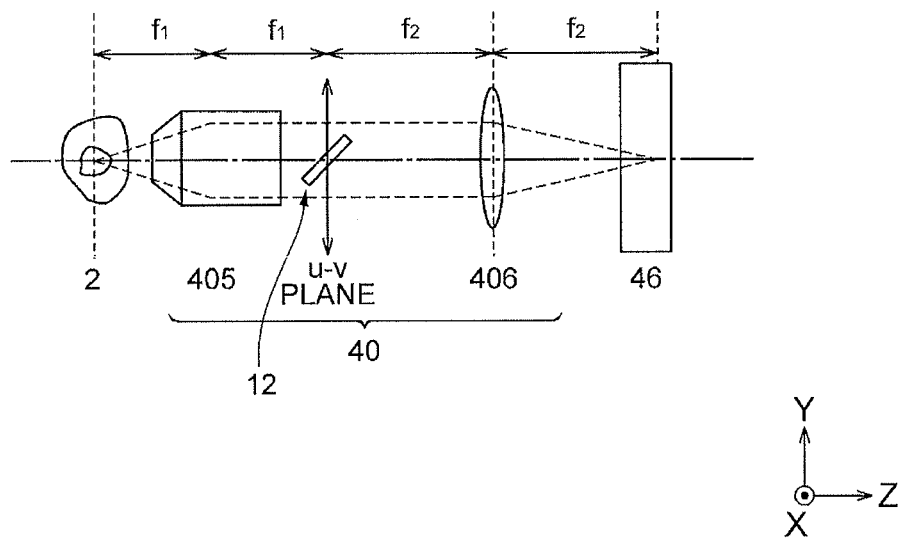
**Fig. 28**

Fig. 29

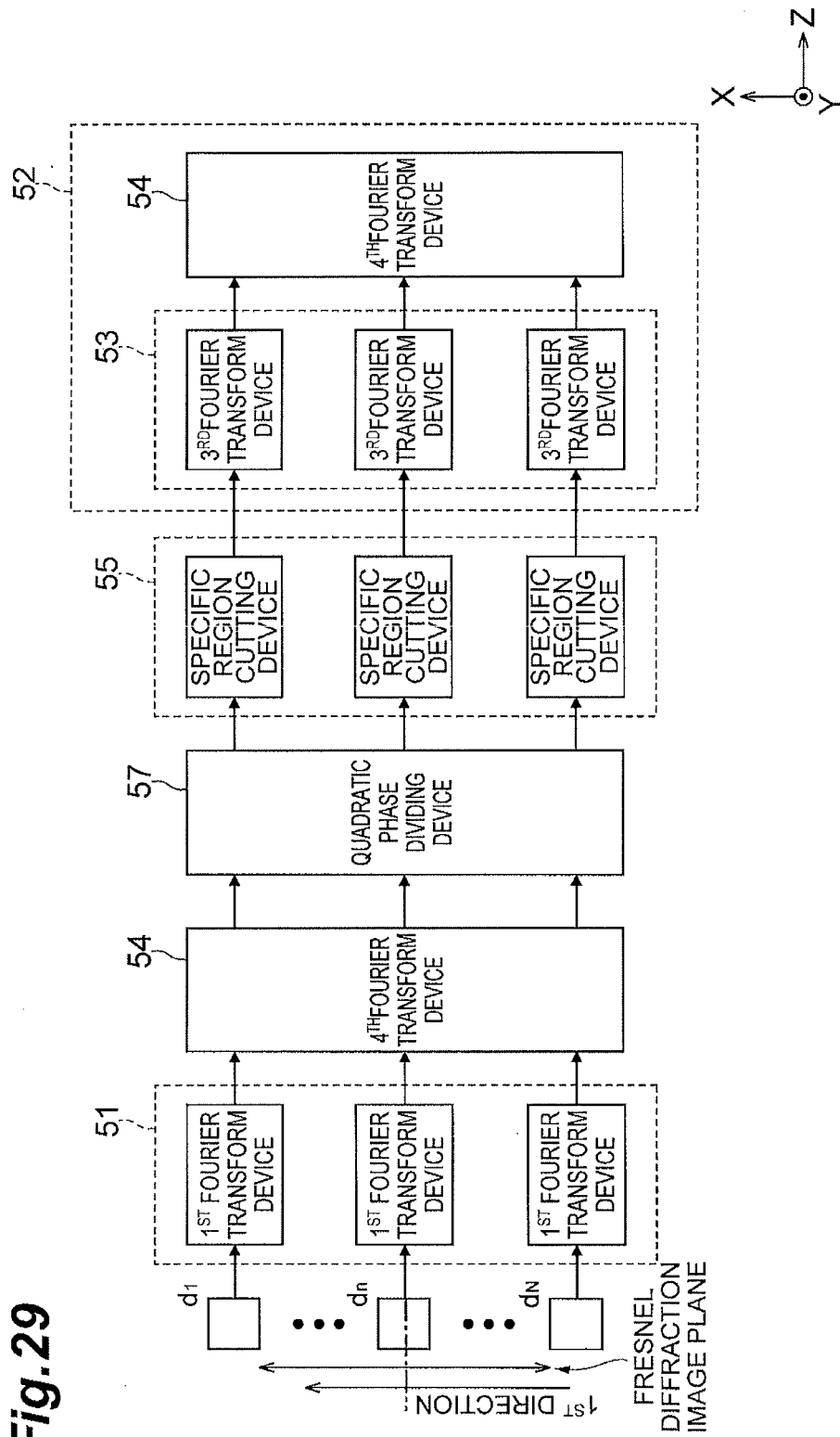


Fig. 30

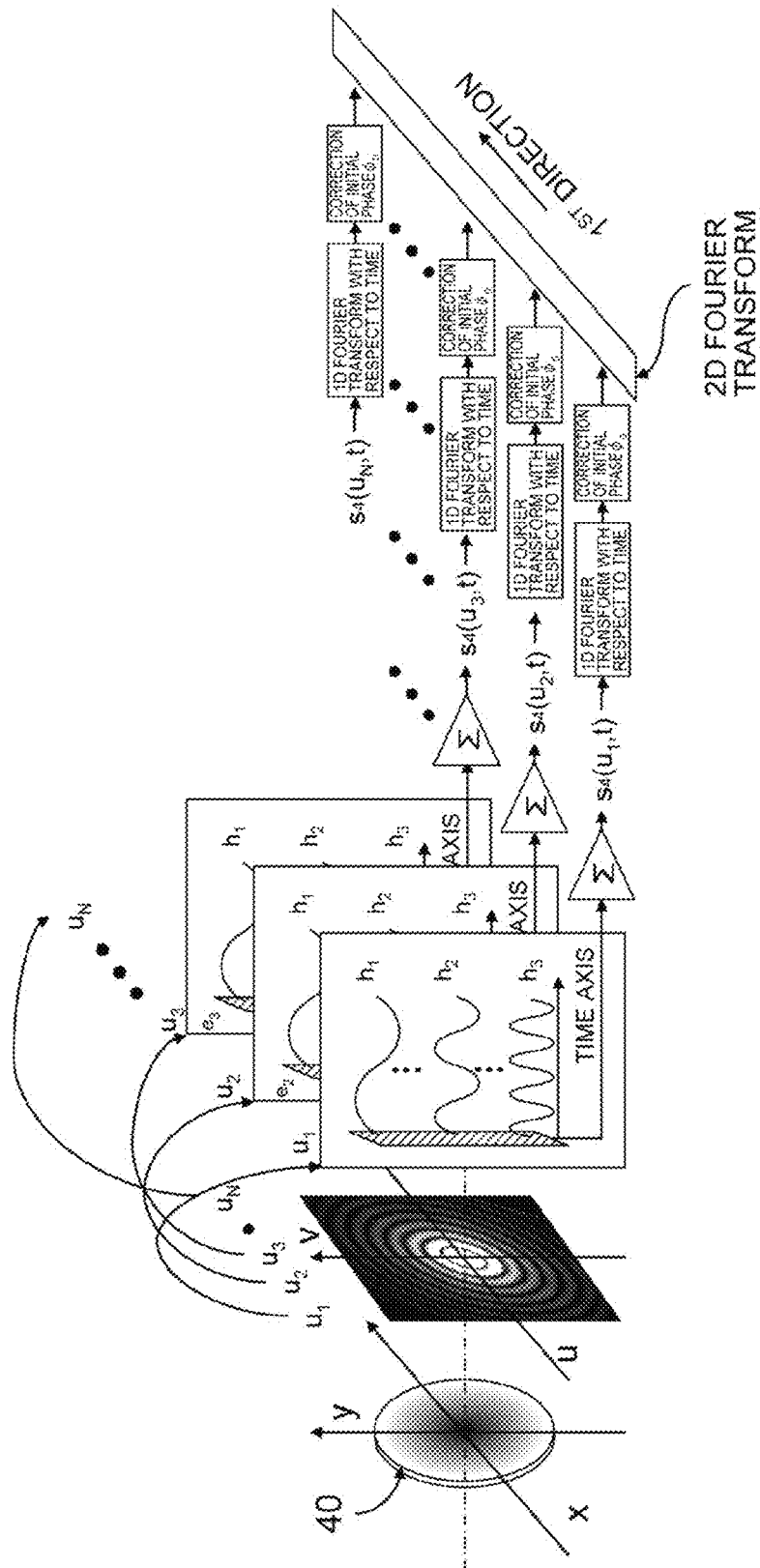




Fig.31

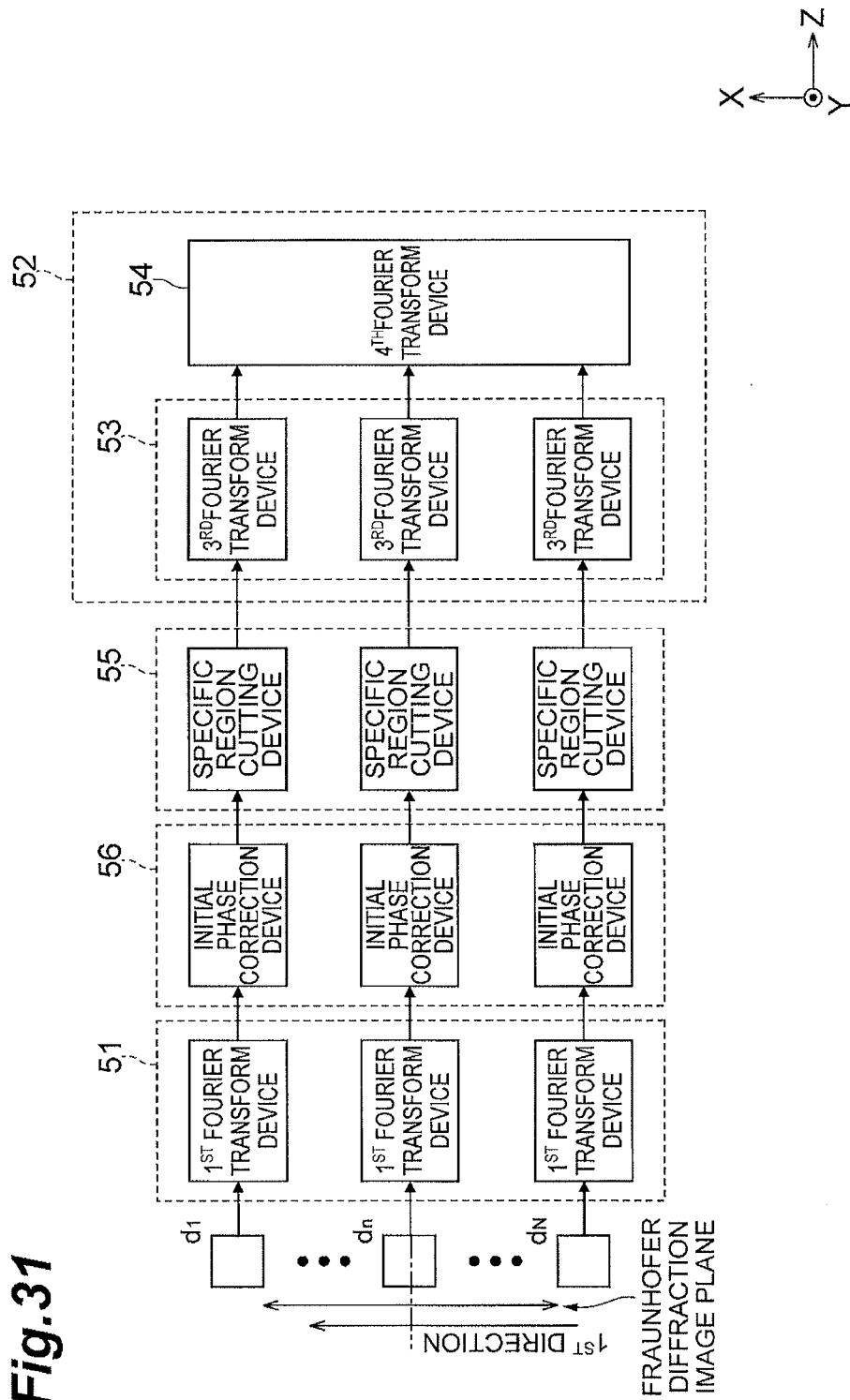


Fig.32

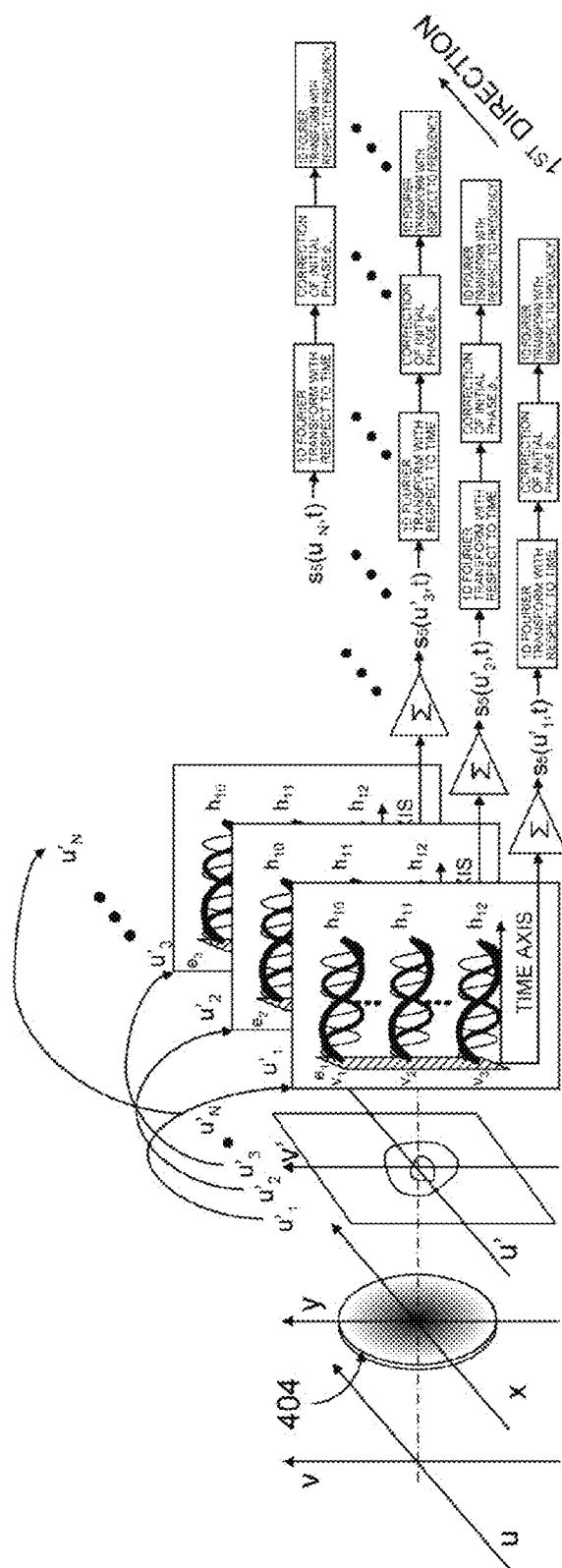


Fig. 33

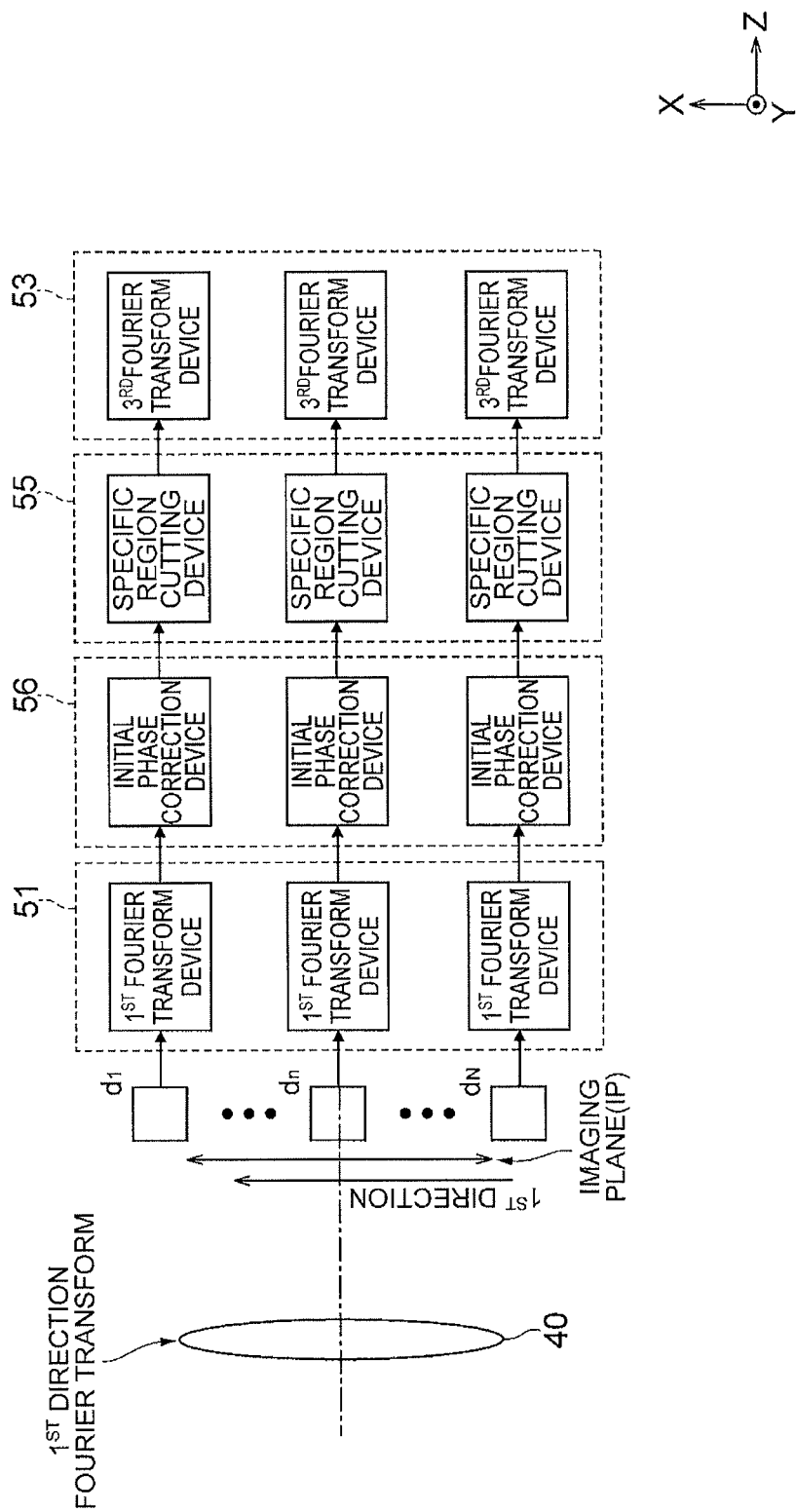


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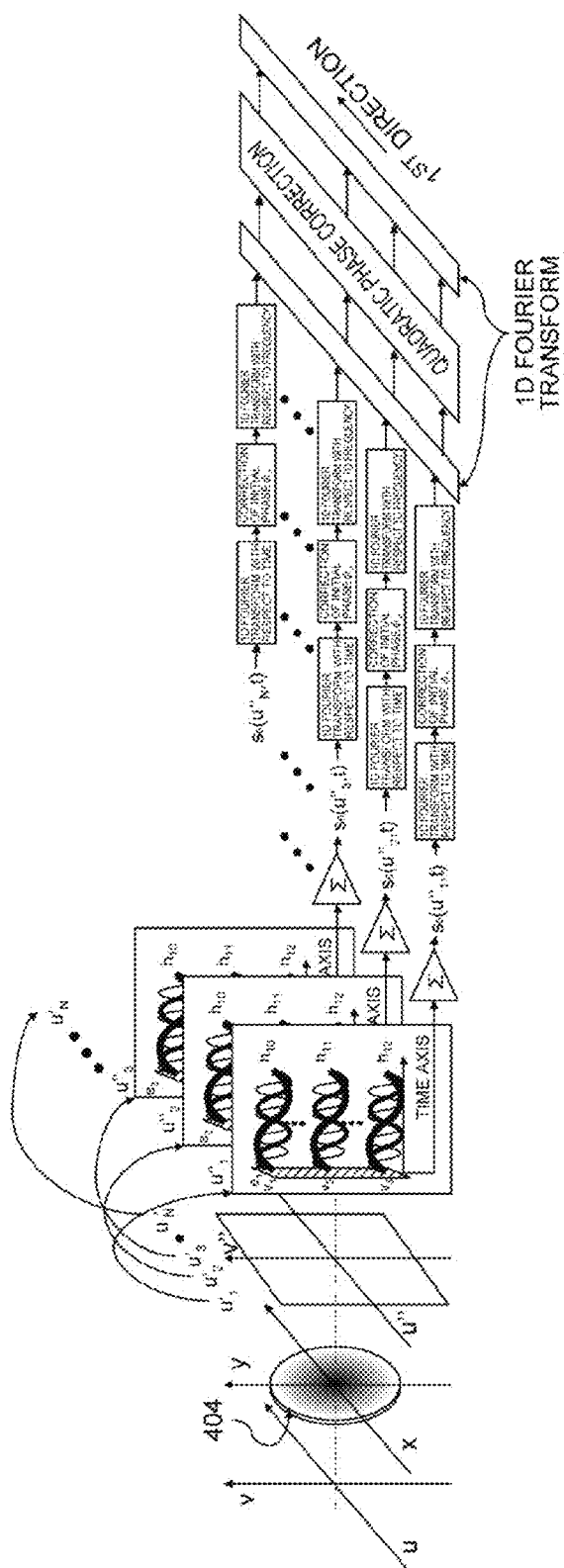


Fig. 35

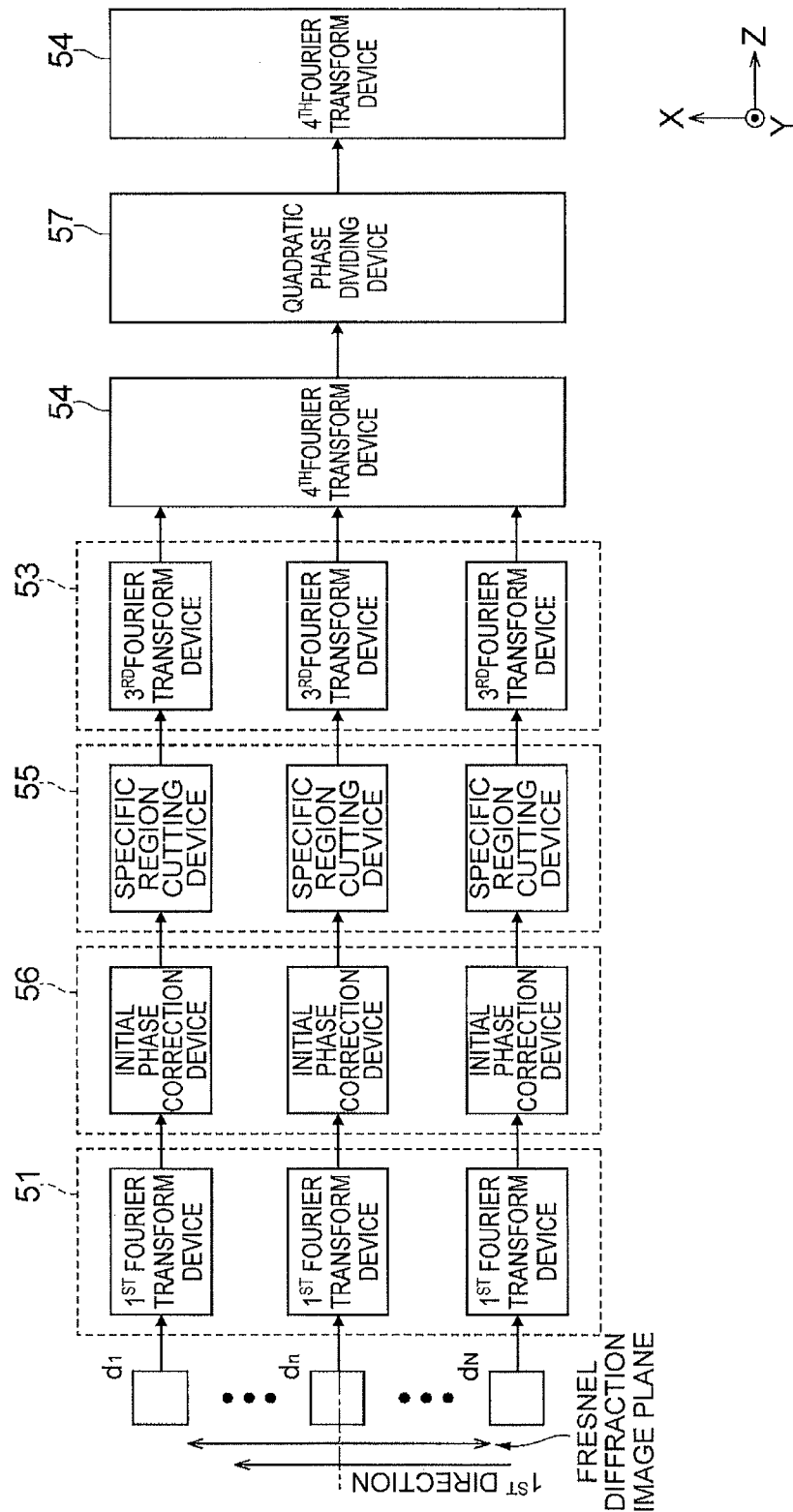


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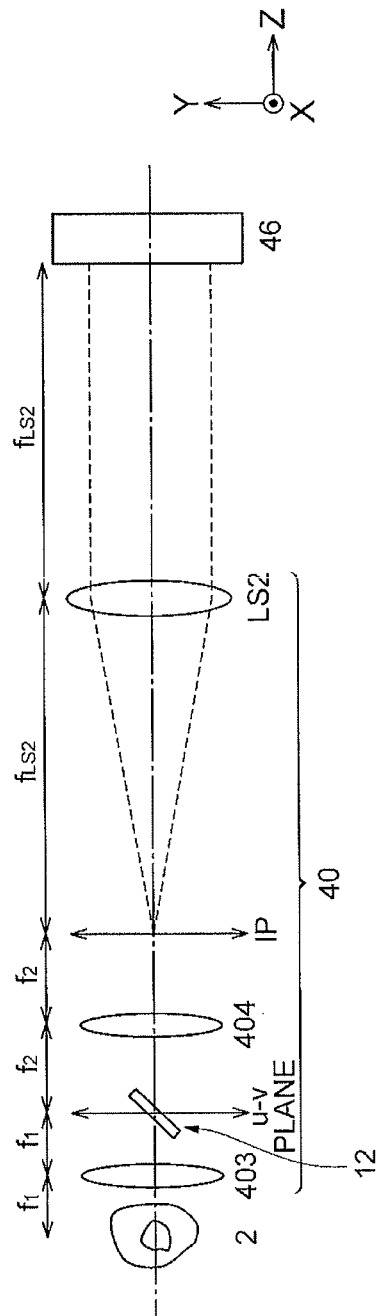
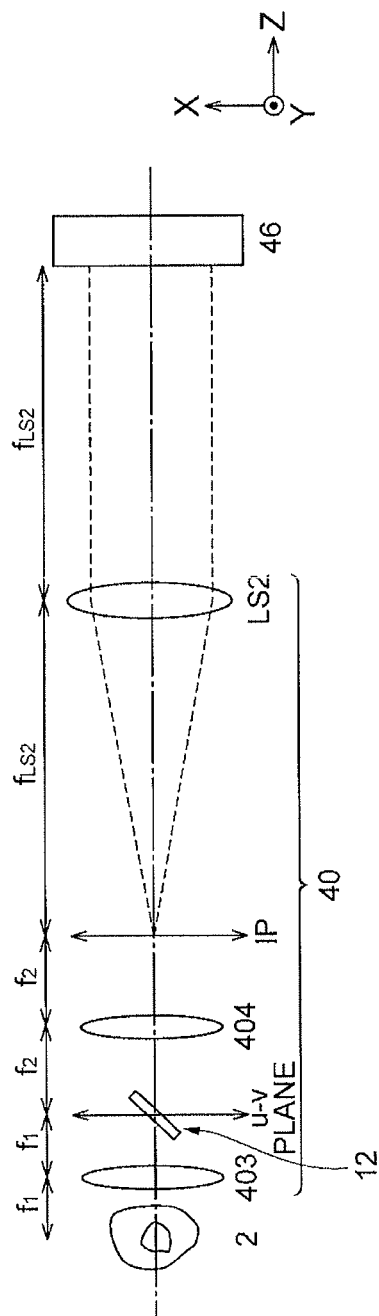


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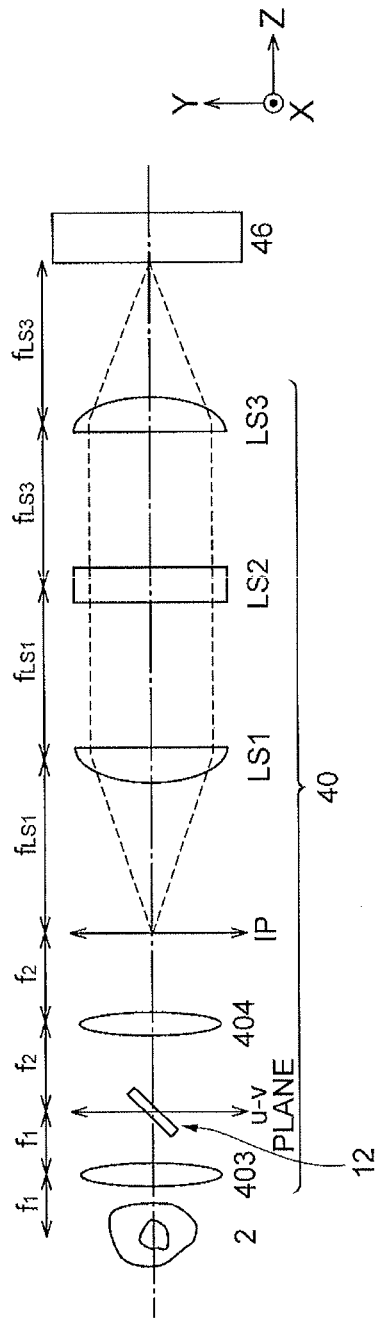
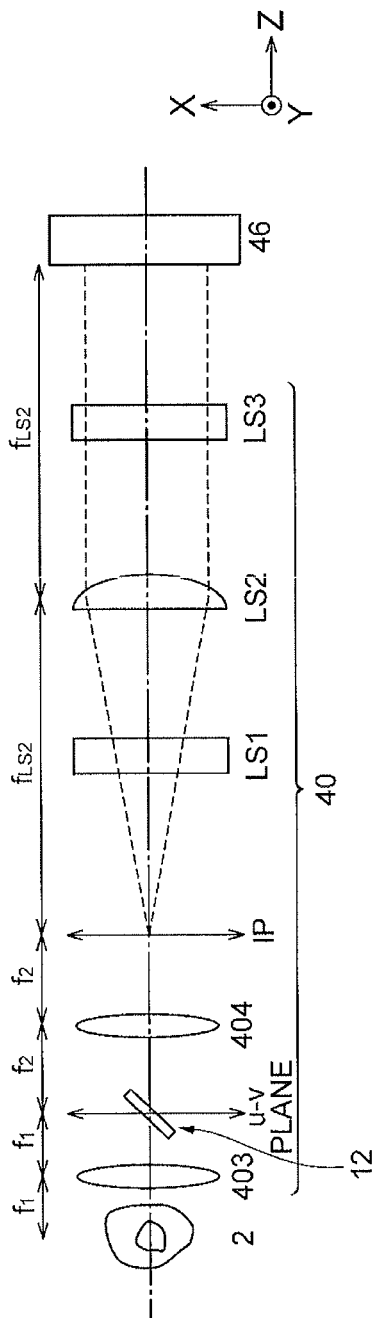


Fig. 38

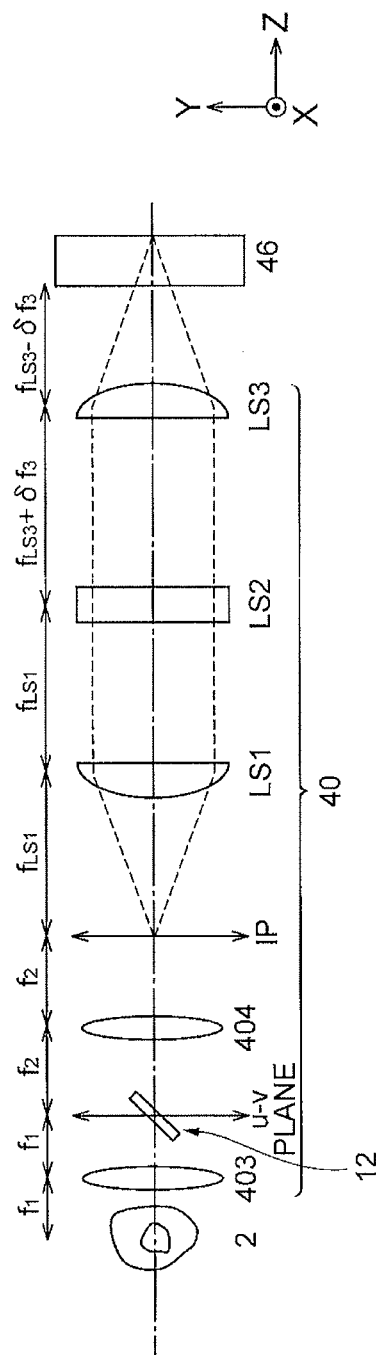
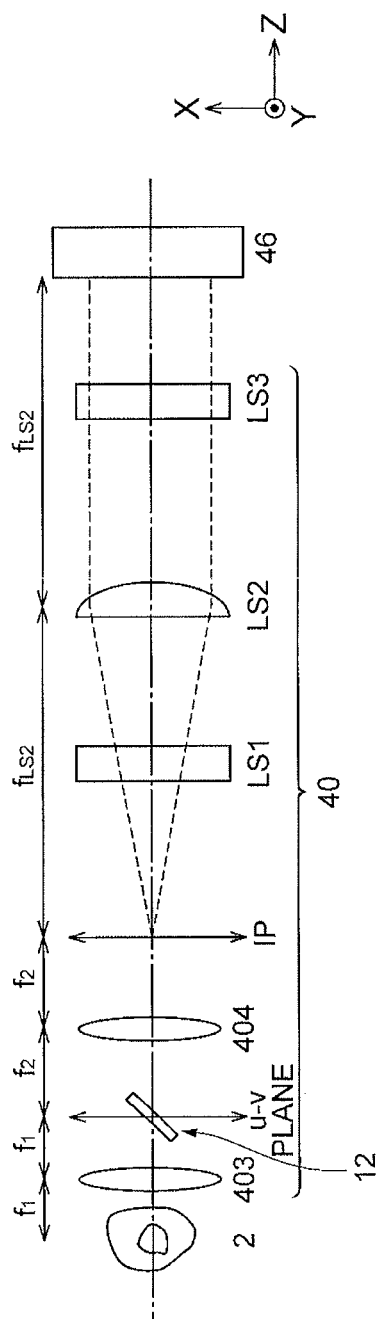
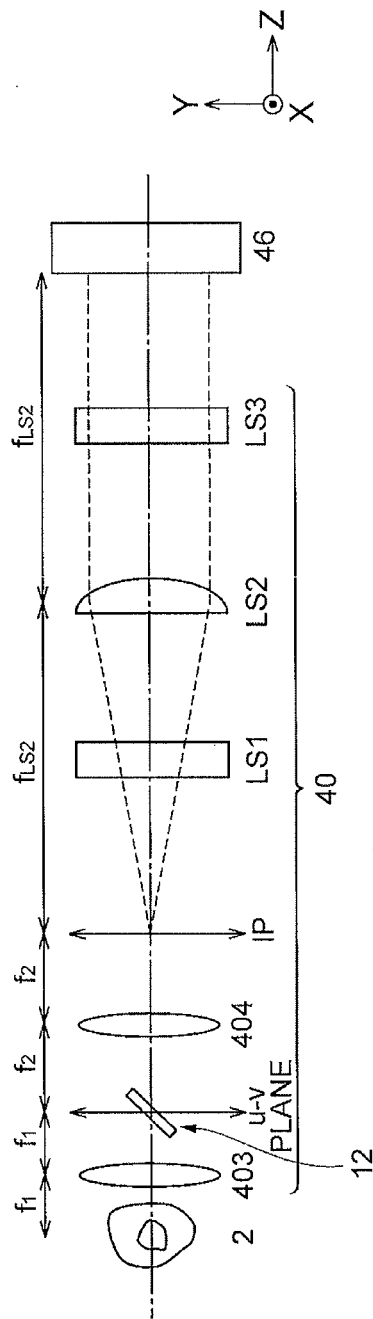
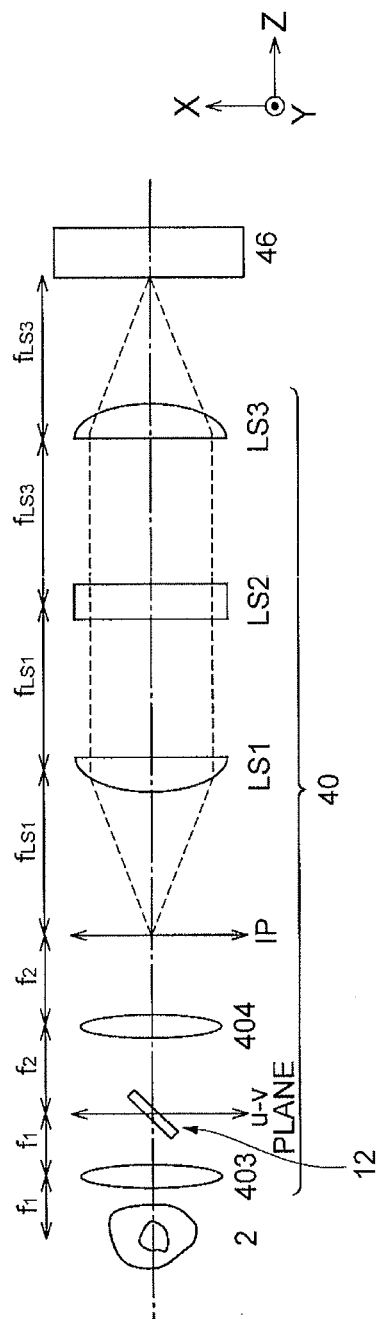




Fig. 39



**Fig. 40**

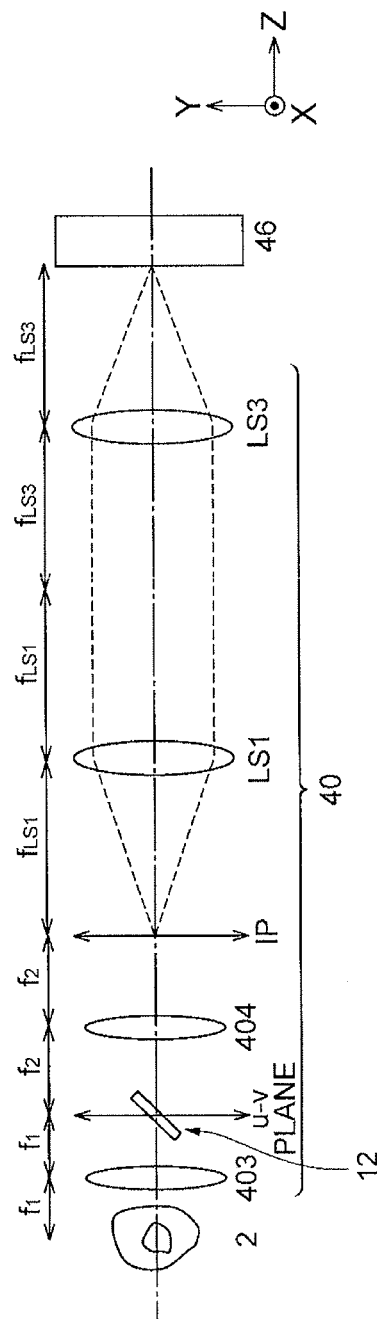
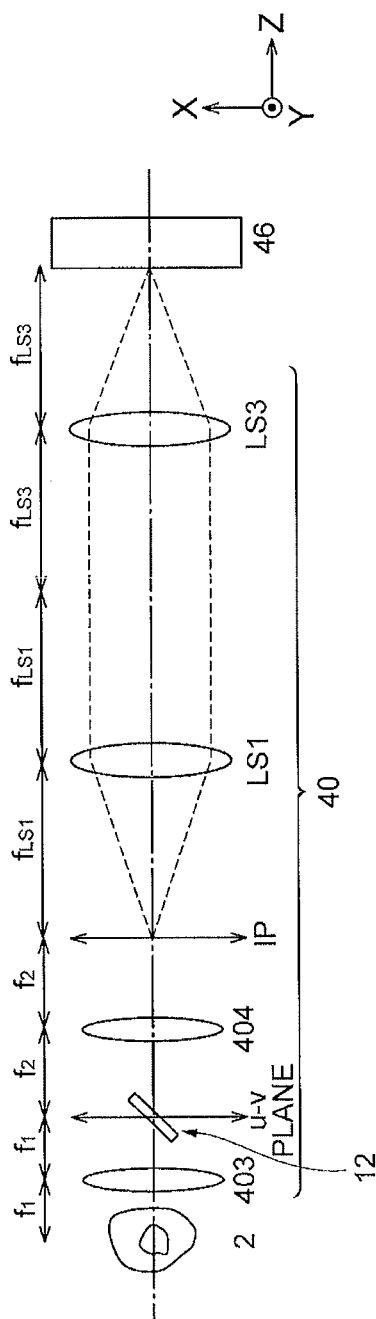


Fig. 41

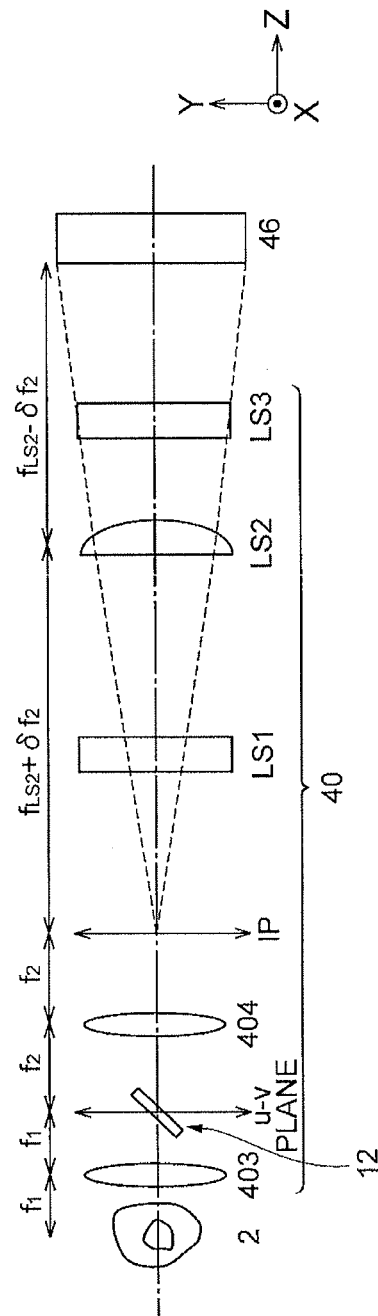
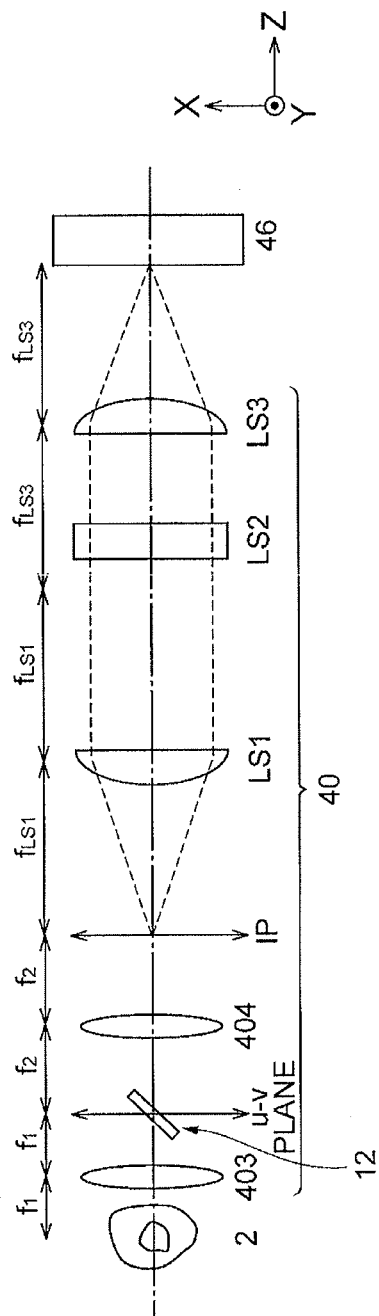




Fig. 43

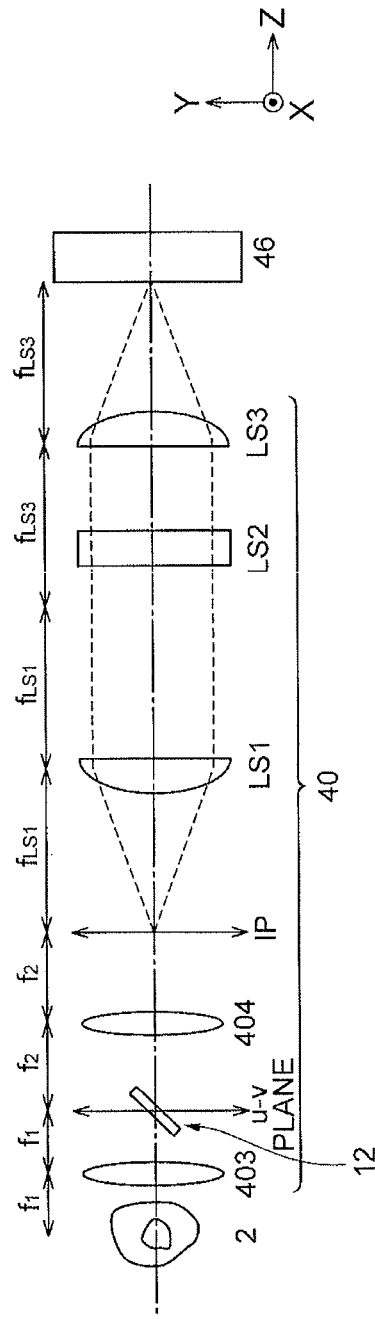
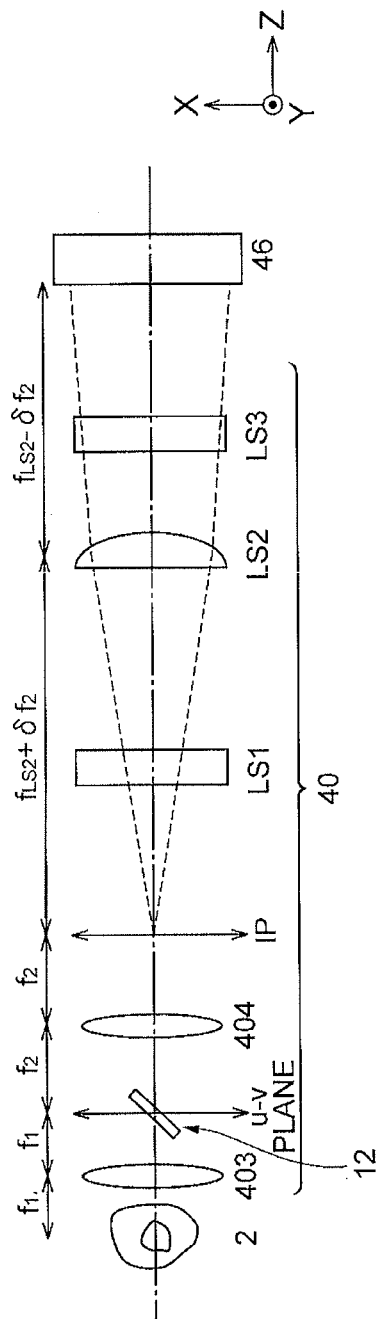
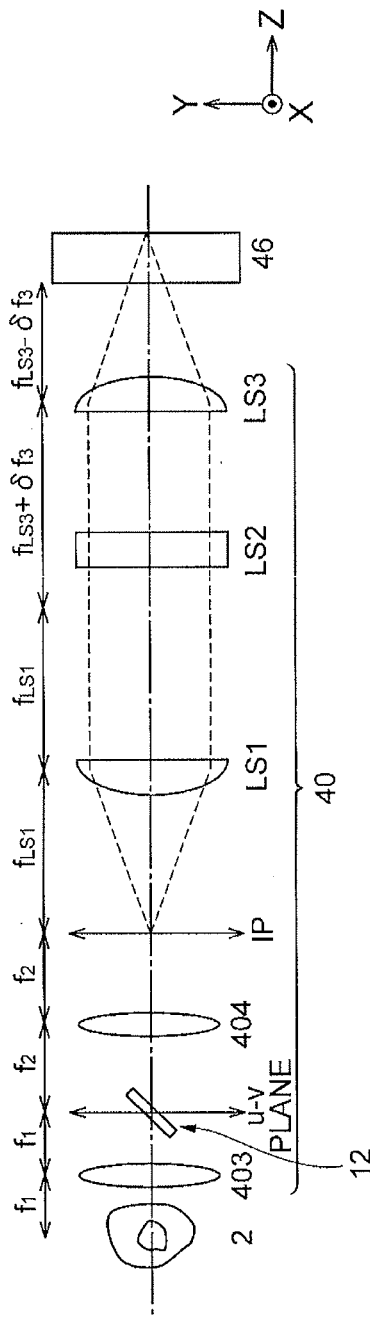
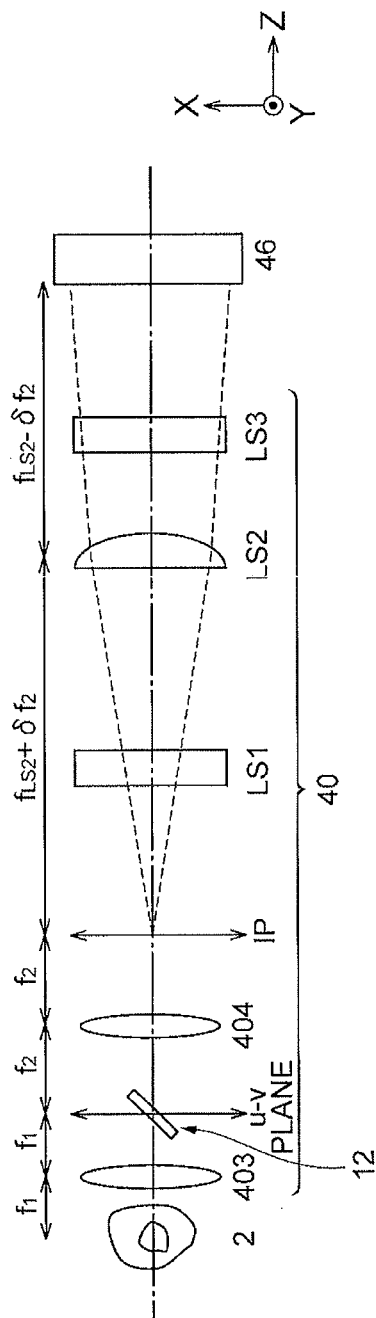


Fig. 44



**Fig.45**

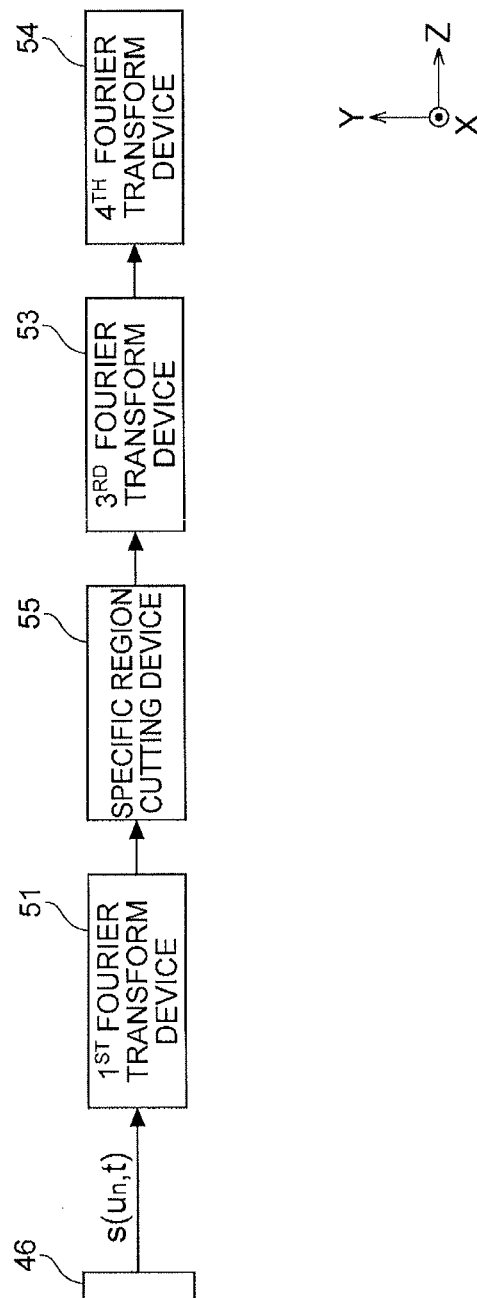


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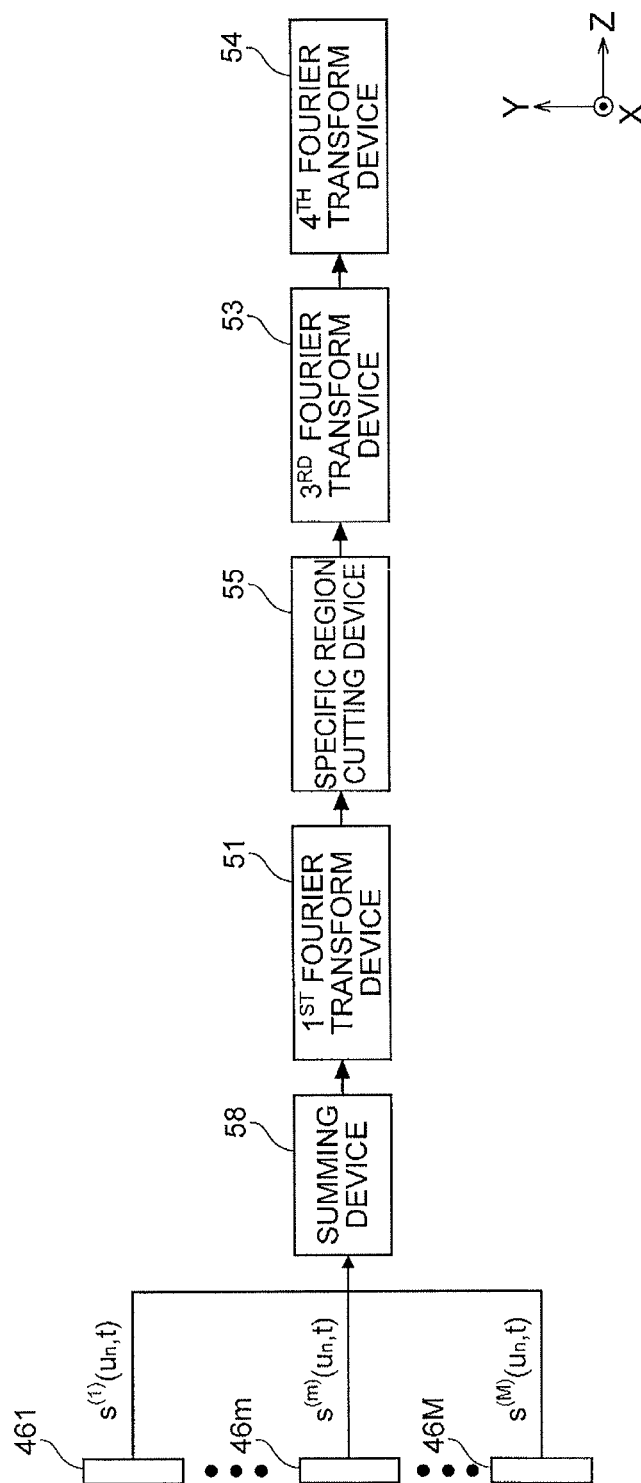




Fig. 47

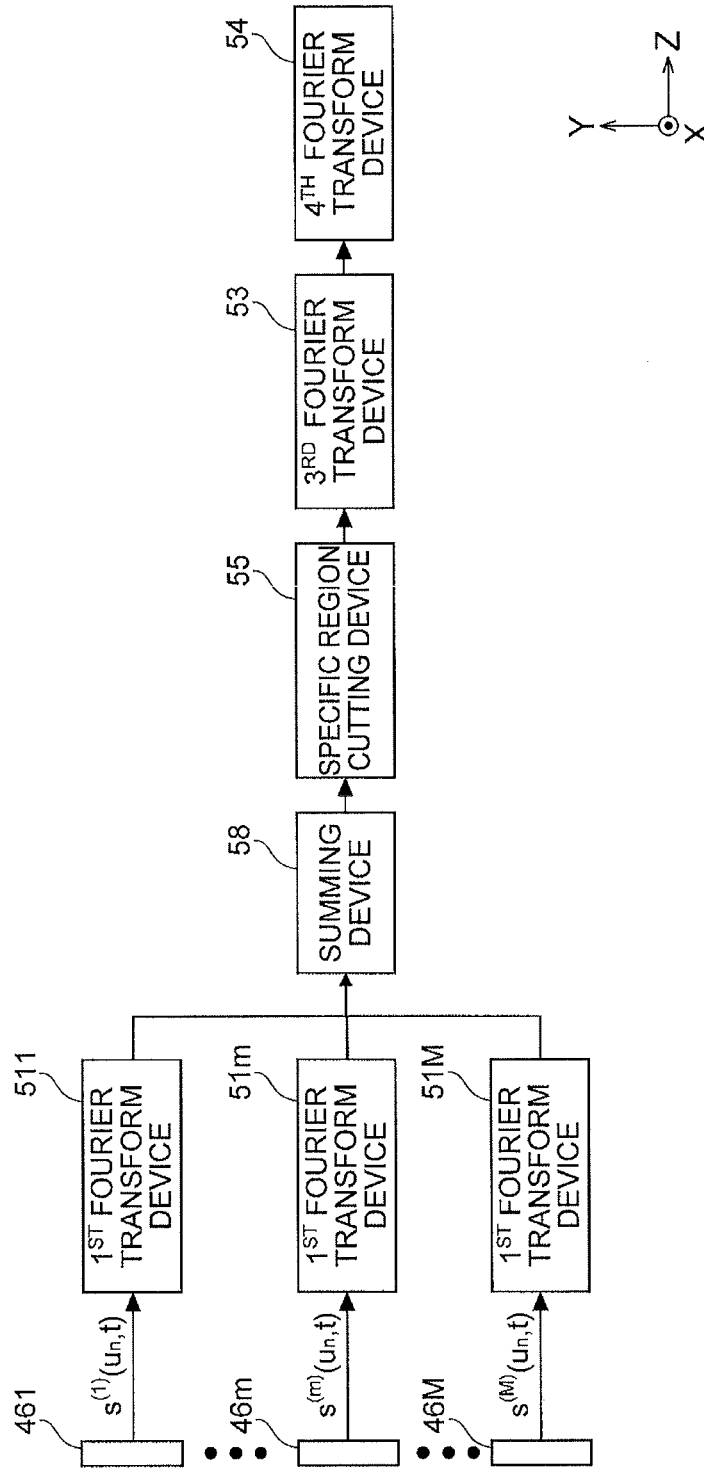


Fig. 48

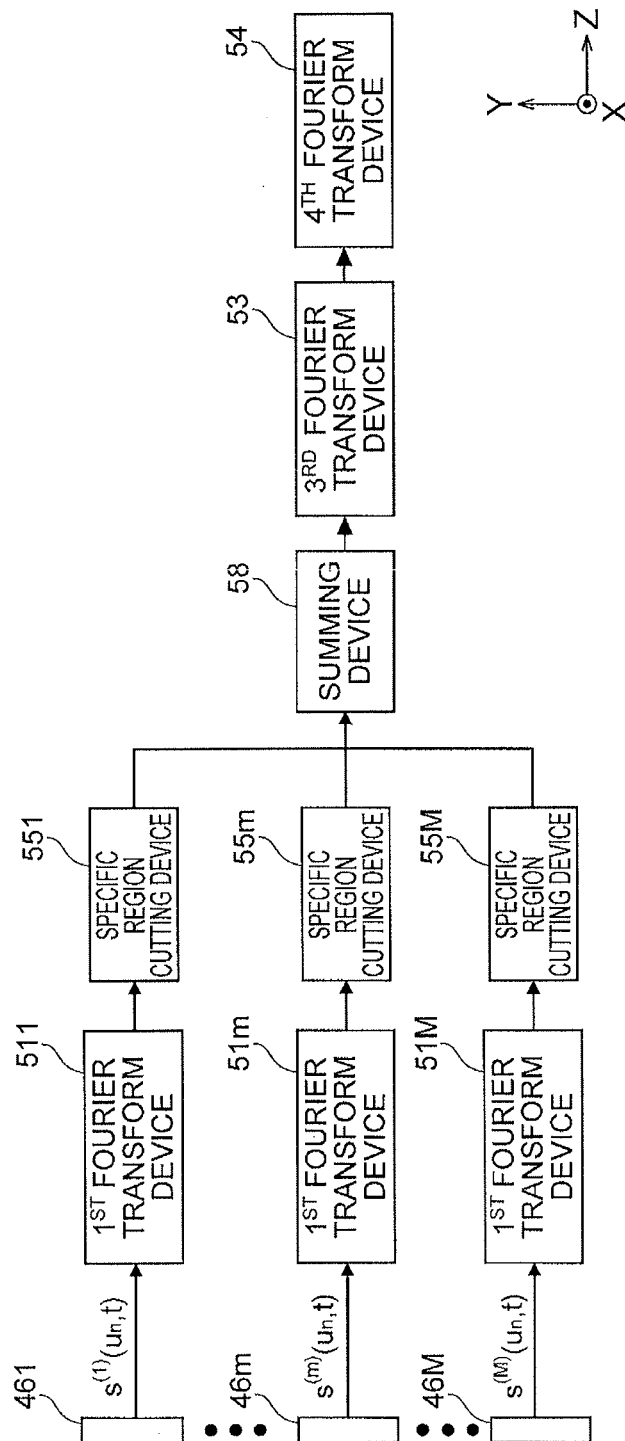
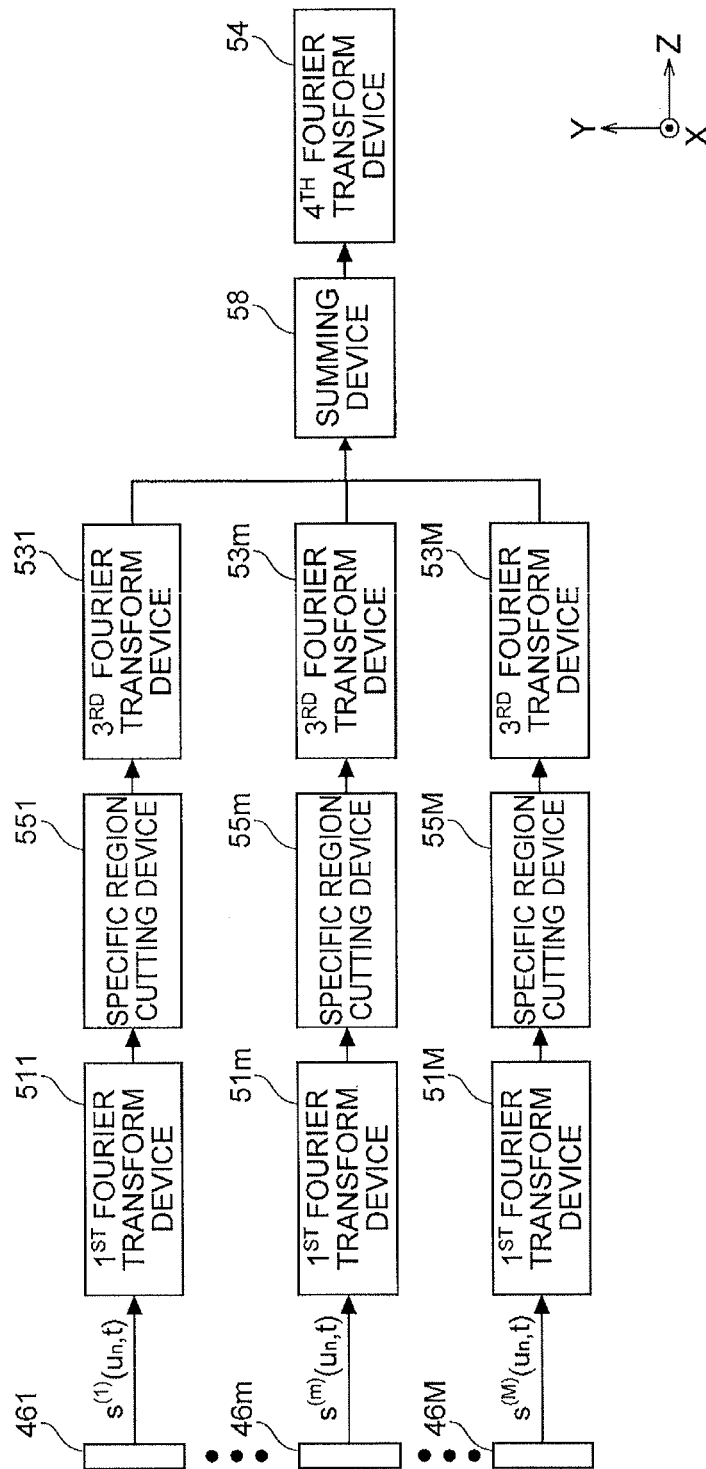
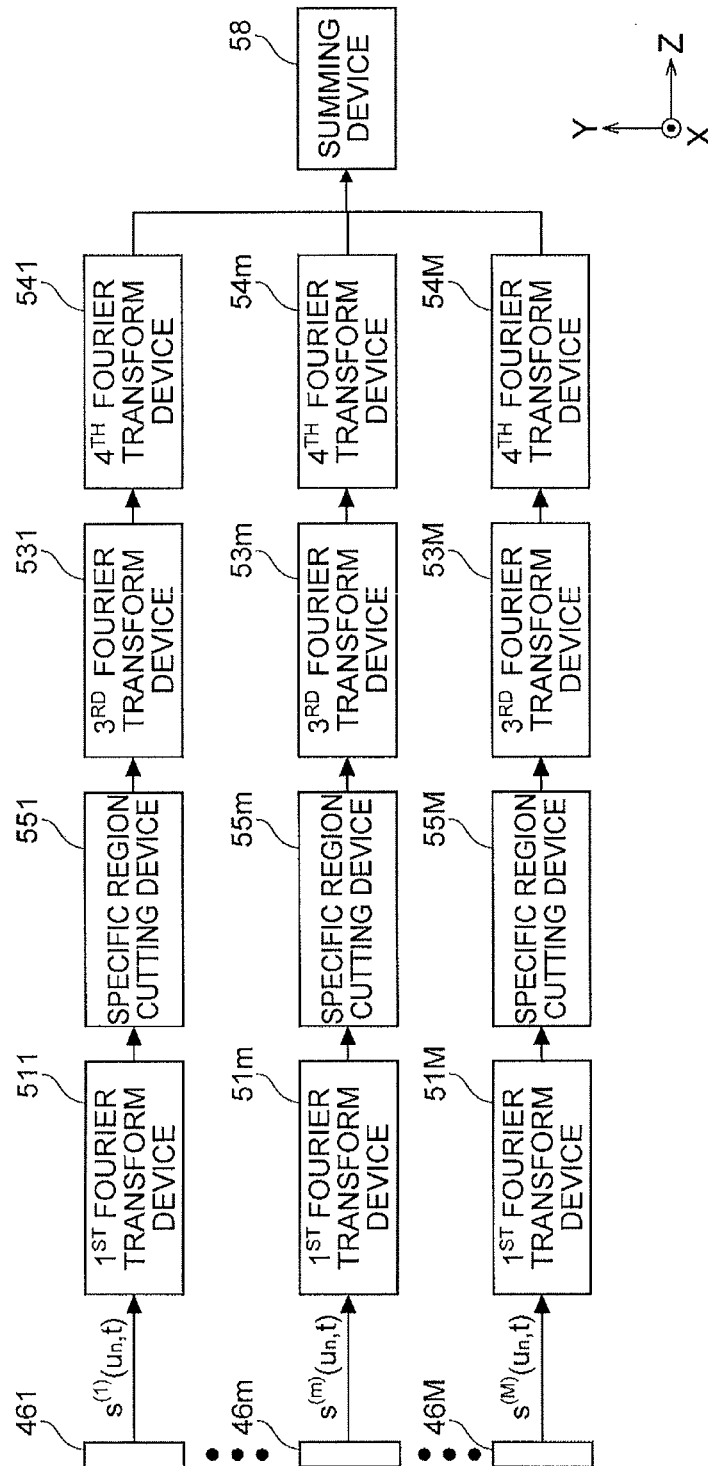
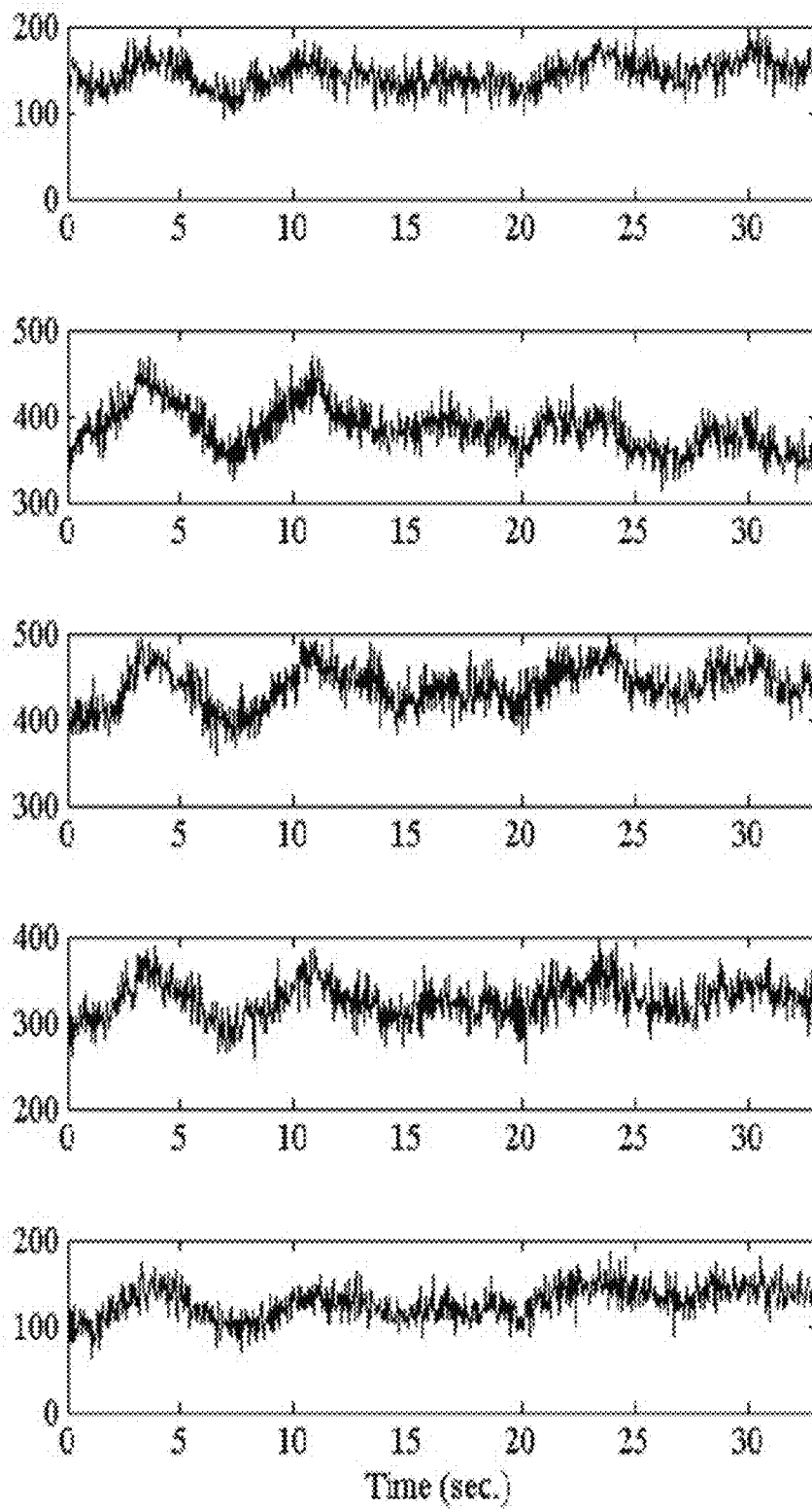


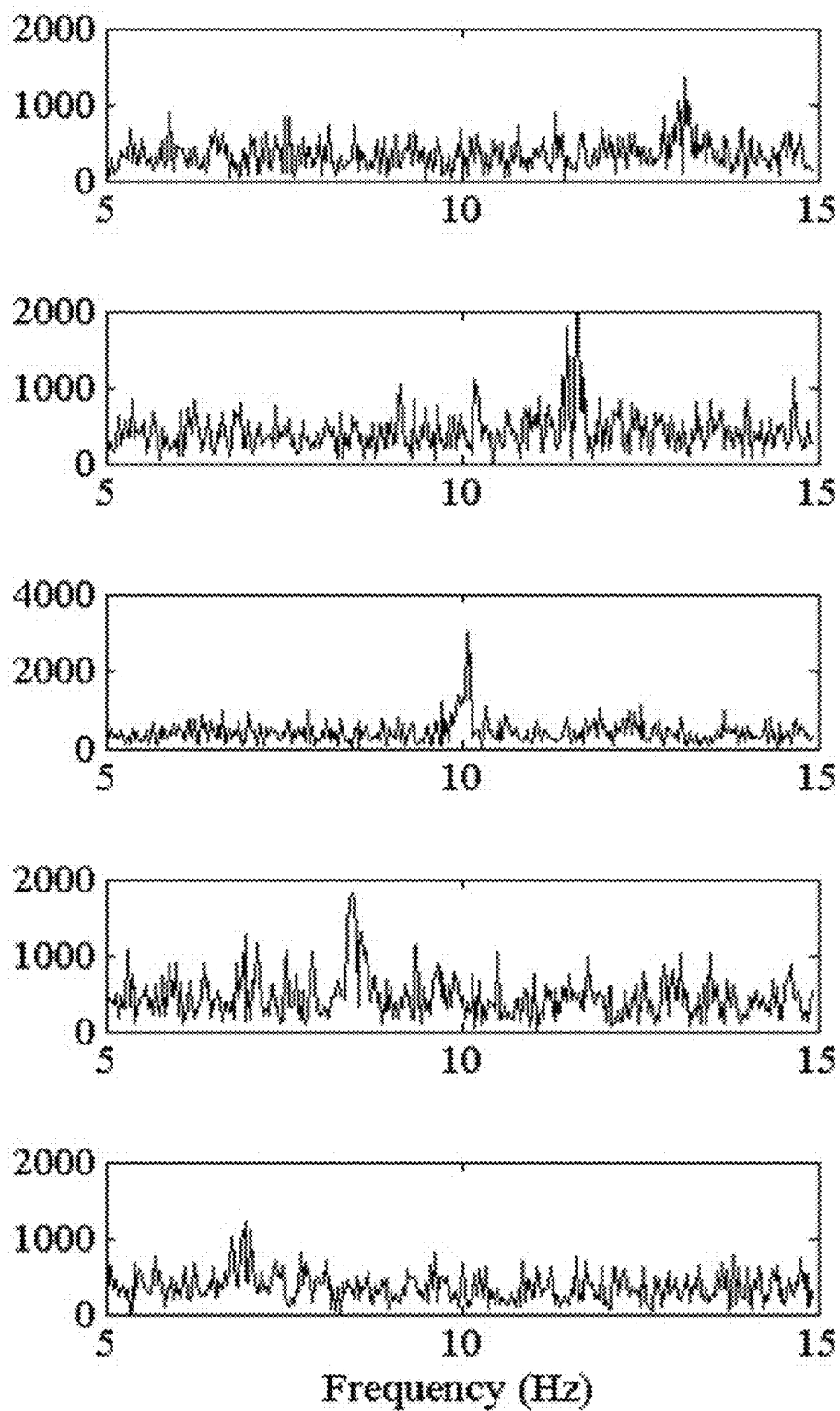
Fig.49

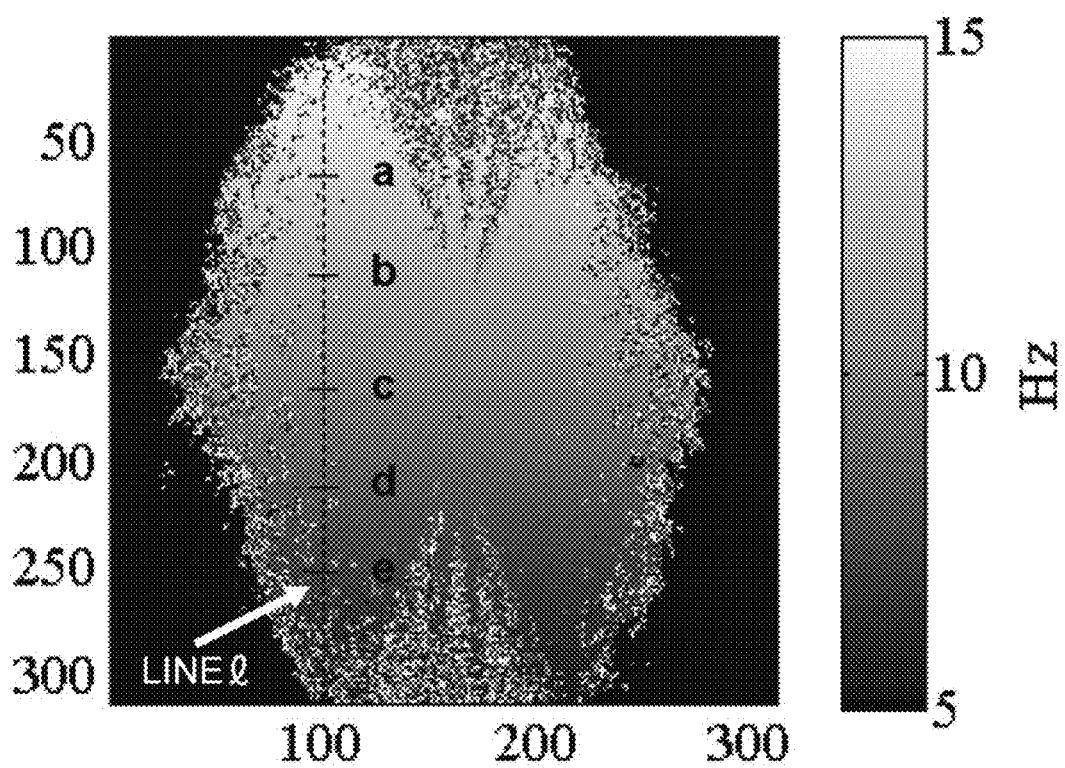


**Fig. 50**

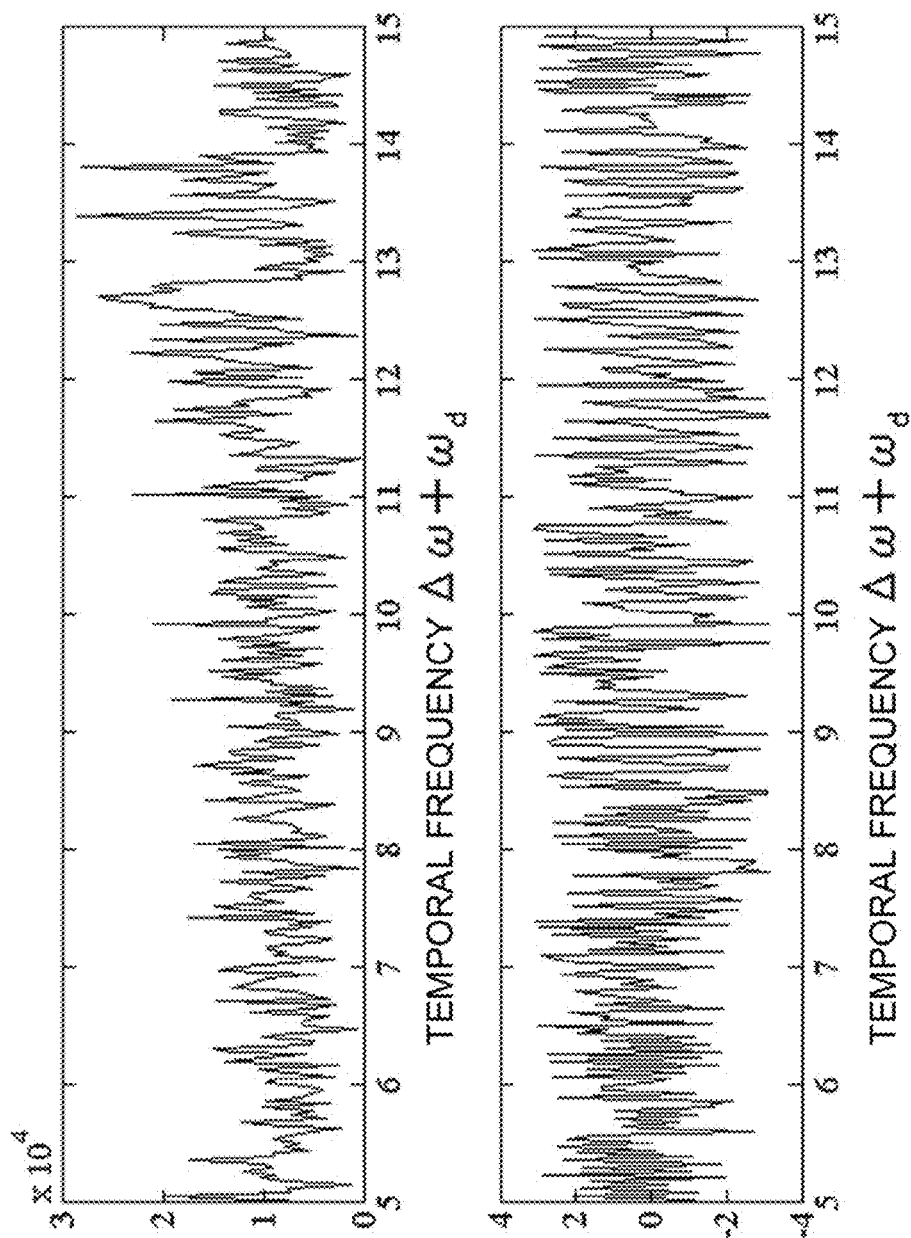


**Fig. 51**

**Fig. 52**

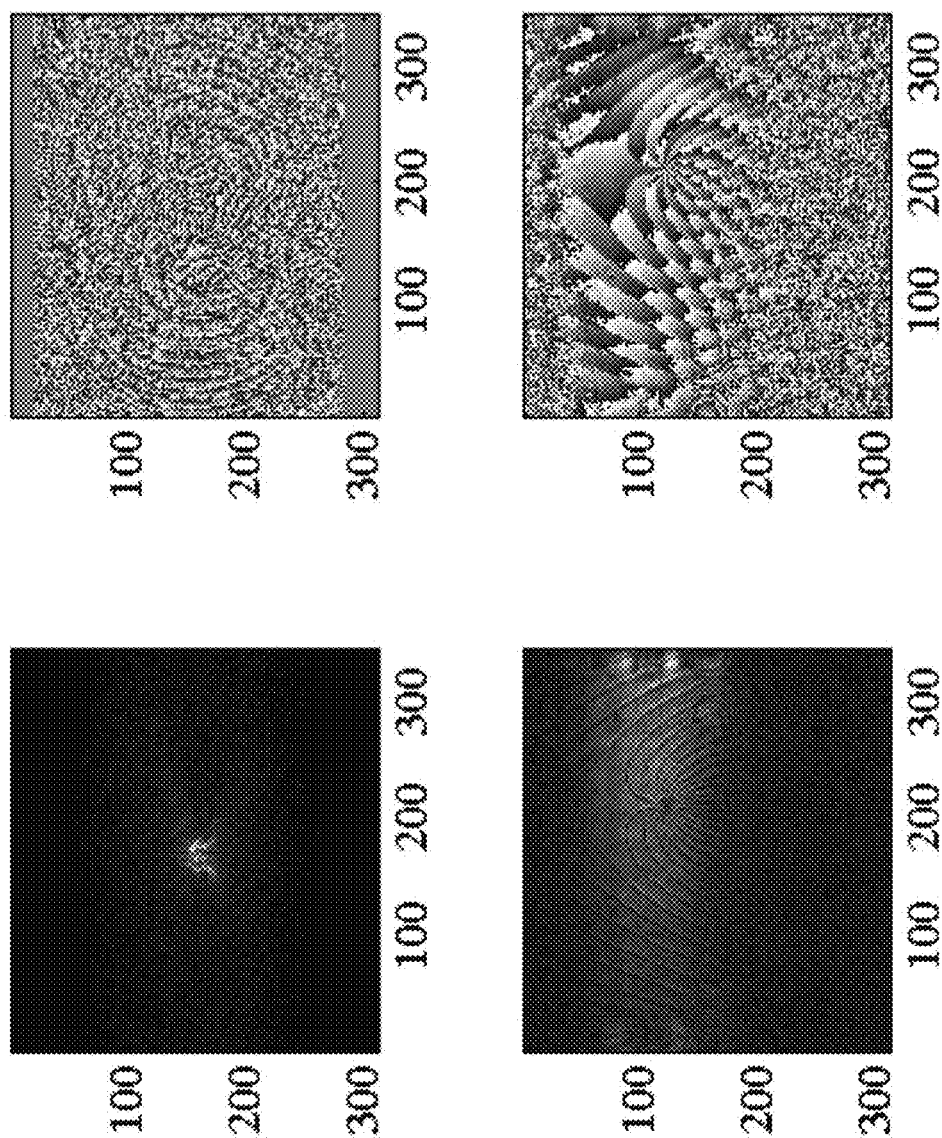
**Fig.53**

**Fig. 54**





**Fig. 55**



**Fig. 56**

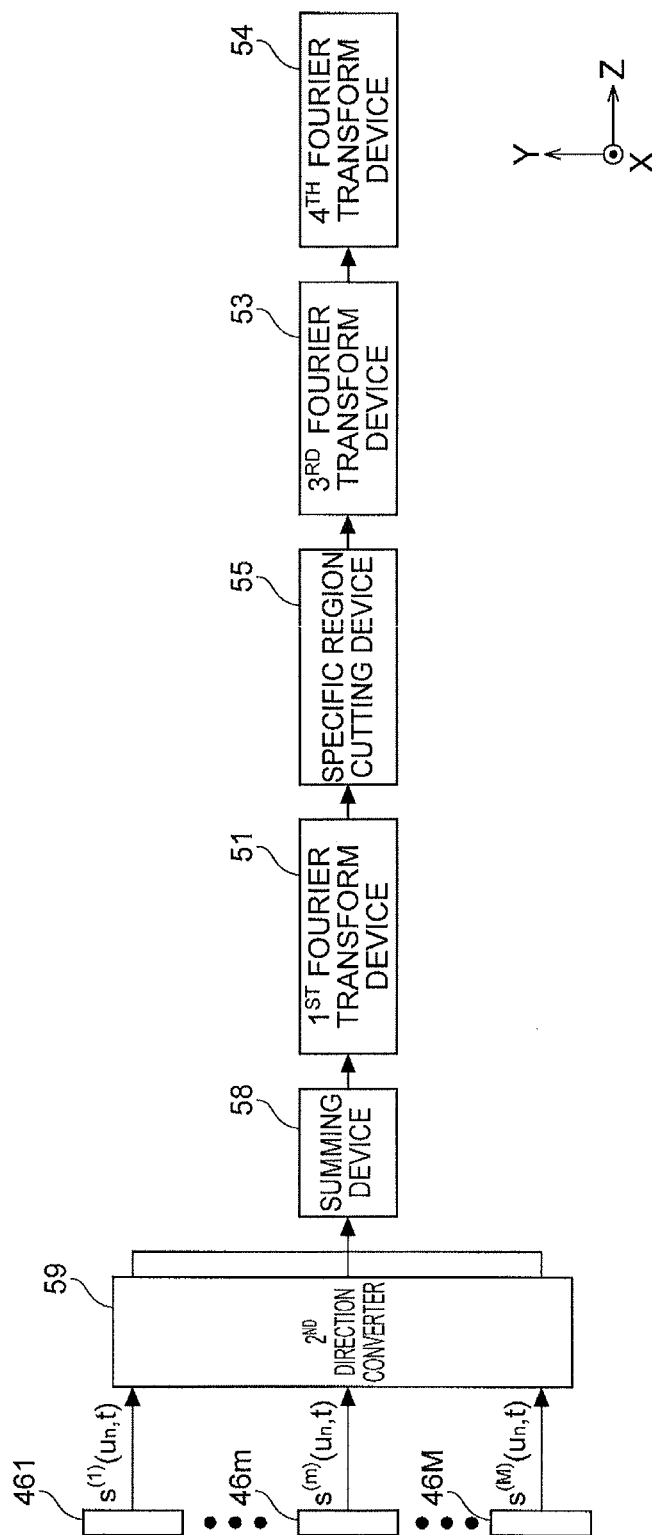


Fig. 57

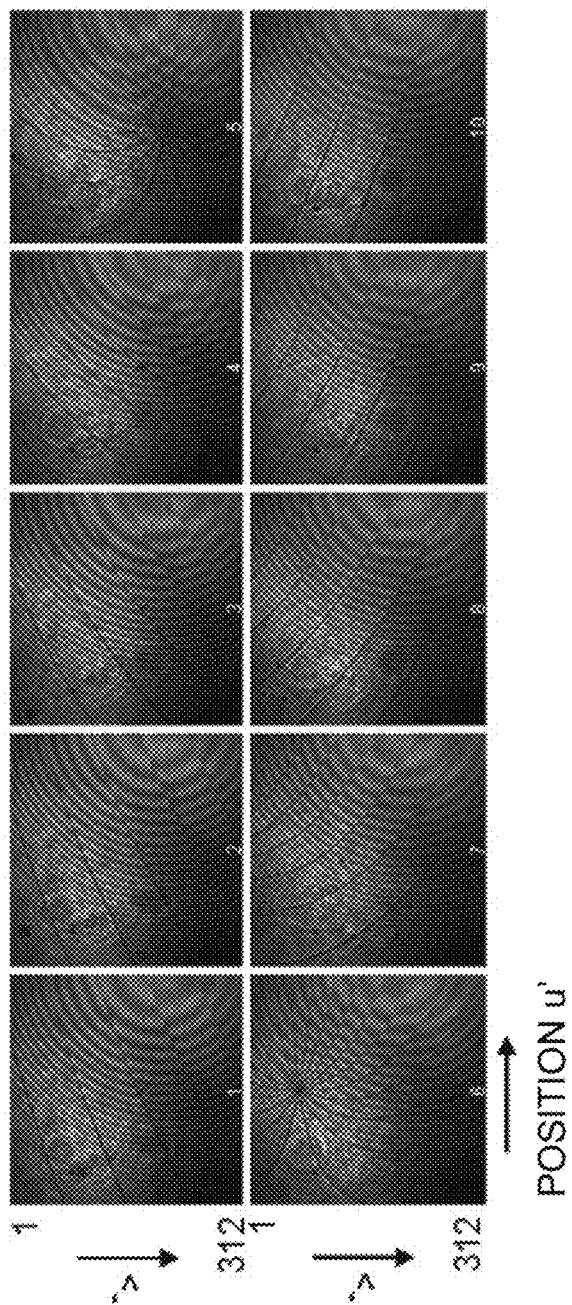


Fig. 58

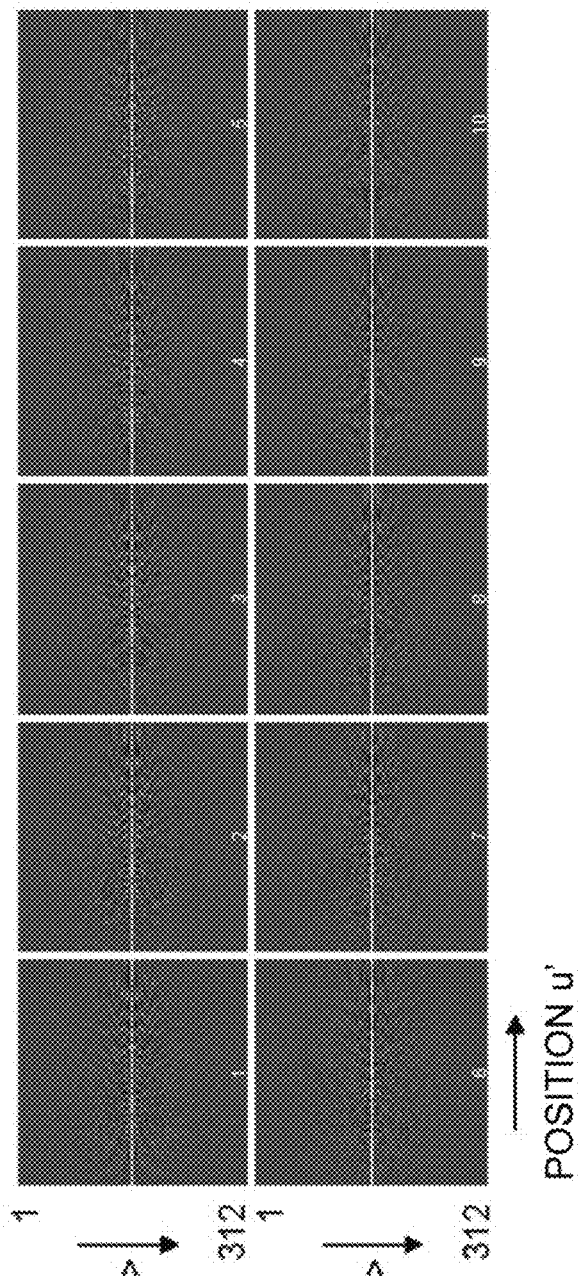
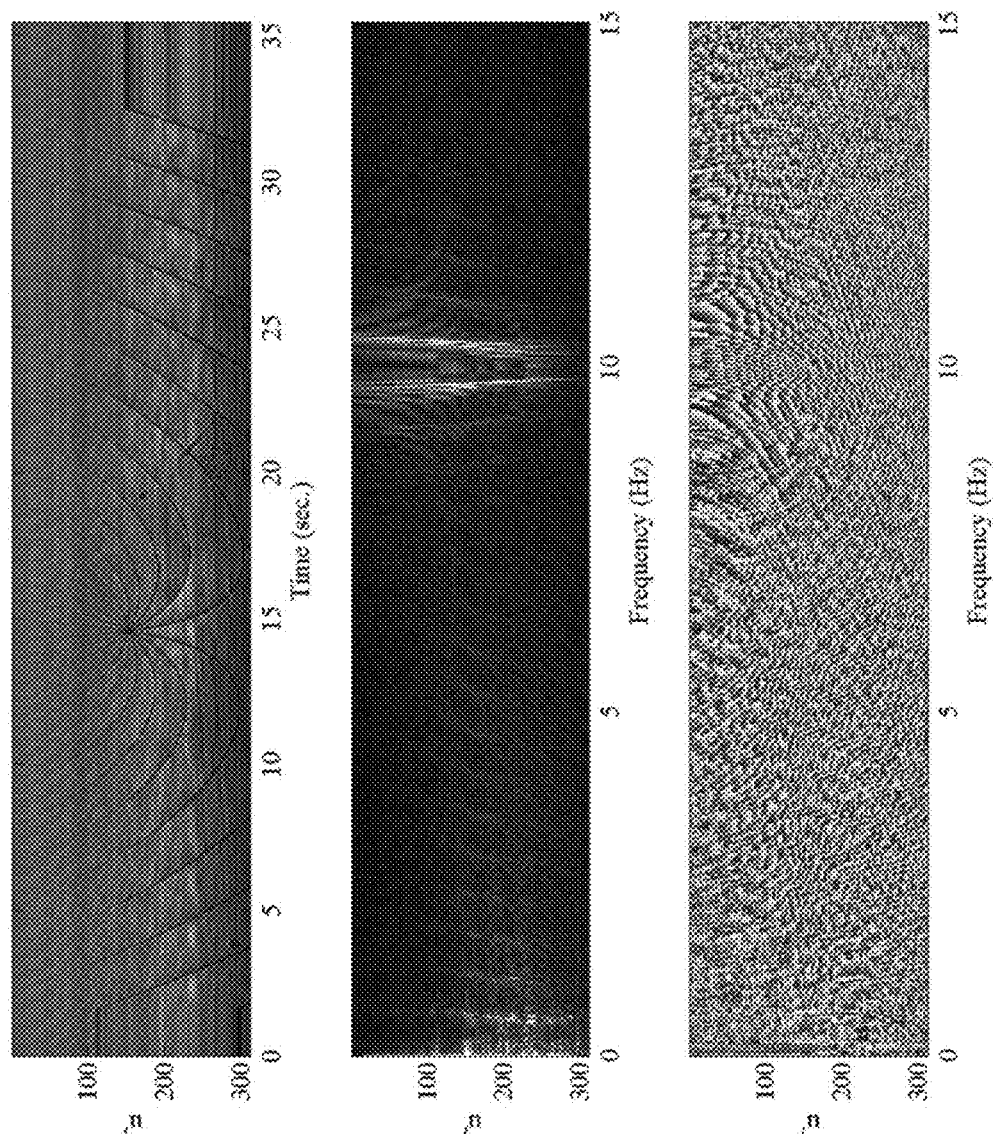


Fig. 59



**Fig. 60**

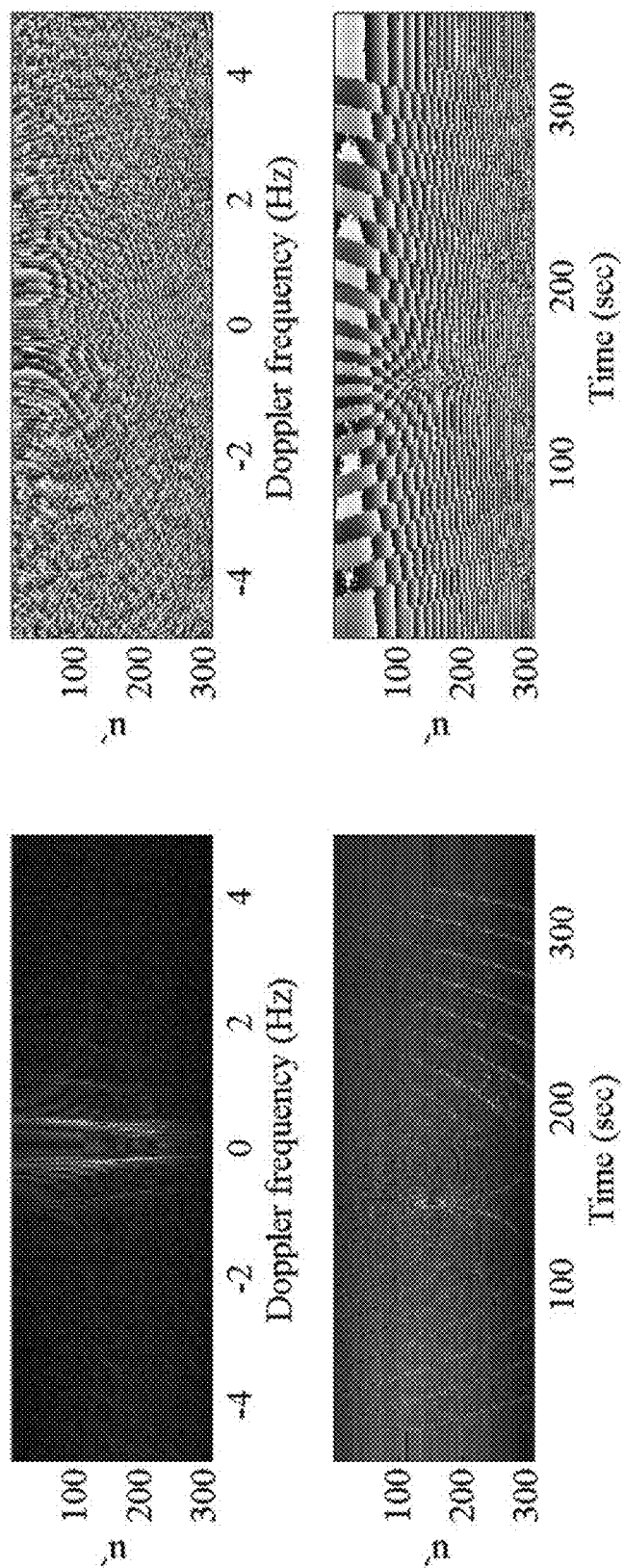


Fig. 61

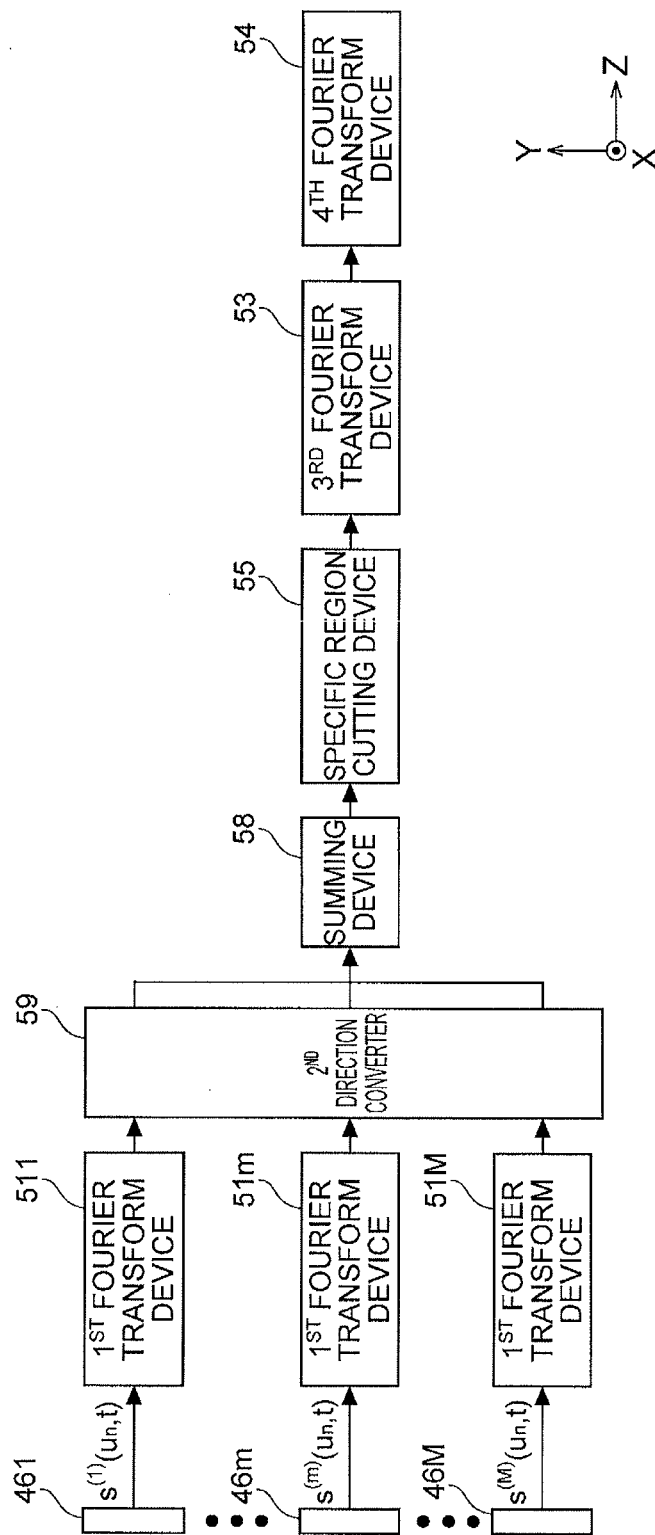


Fig. 62

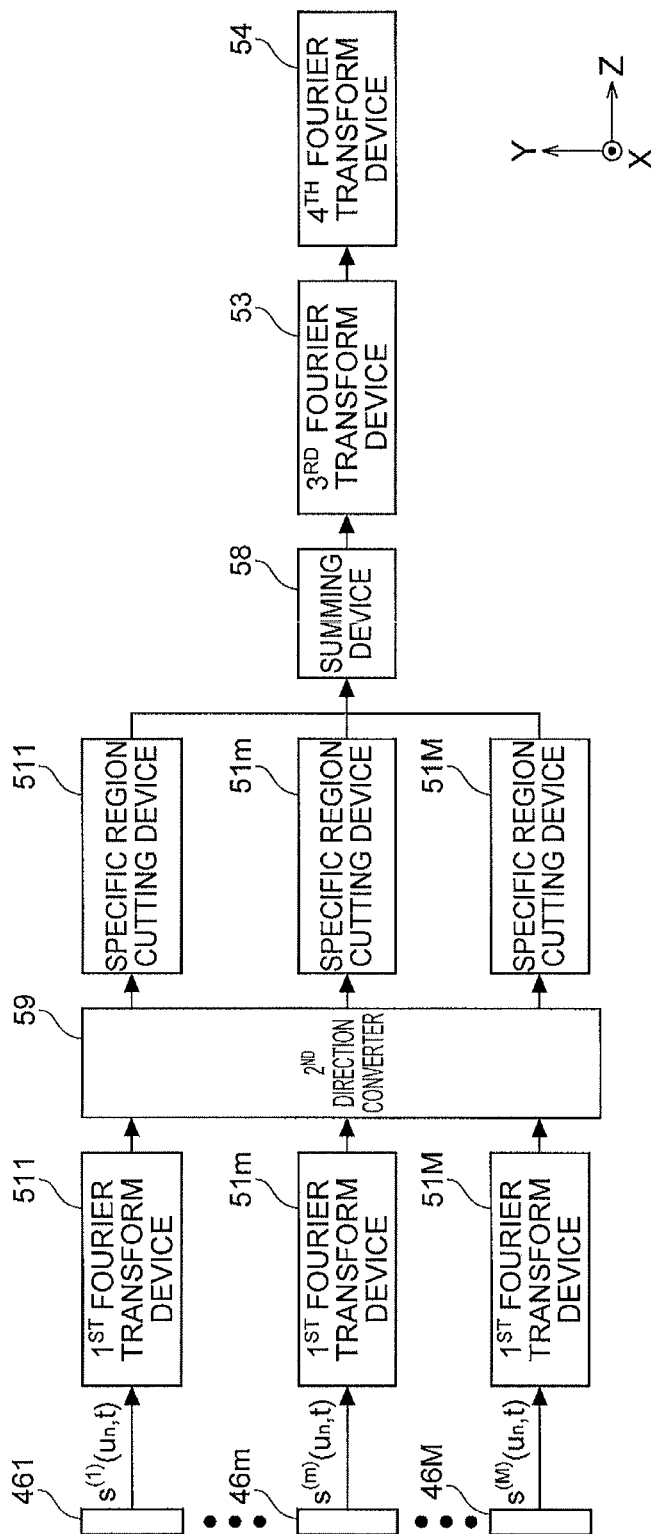
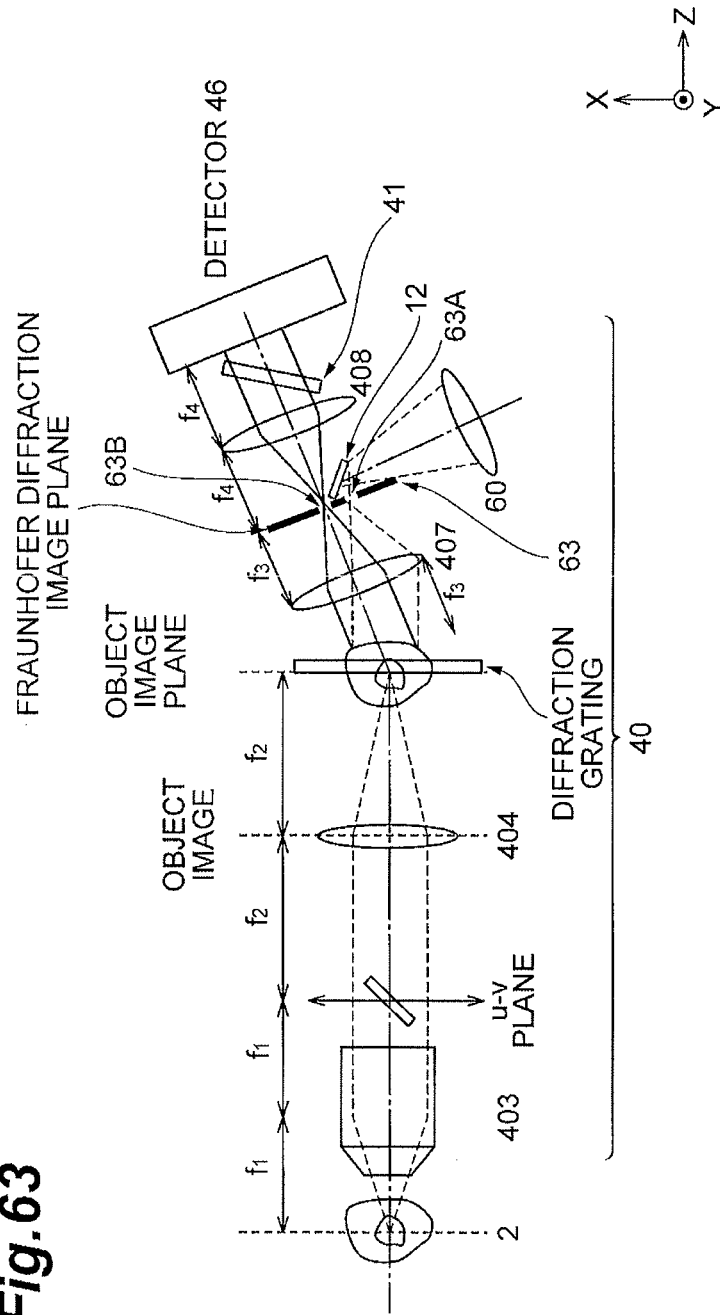




Fig. 63



1

**PHASE IMAGE ACQUISITION DEVICE****TECHNICAL FIELD**

The present invention relates to an observation device for  
observing a phase image of an object.

**BACKGROUND ART**

Colorless, transparent objects (phase objects) such as cells  
and glass bodies, which are hard to observe according to an  
intensity distribution (amplitude image) of transmitted light  
occurring when the objects are irradiated with light, are  
observed according to a phase distribution (phase image) of  
the transmitted light. Examples of devices for observing the  
phase image of such an object include phase contrast micro-  
scopes and differential interference microscopes. However,  
these devices cannot obtain quantitative information about  
the optical thickness of the objects.

As techniques for obtaining quantitative information by  
observing a phase image of an object, those using phase shift  
methods described in Patent Literature 1 and Non Patent  
Literature 1 have been known. In observation devices based  
on these phase shift methods, light having a wavelength  $\lambda$   
emitted from a light source is split in two, one split light is  
transmitted through the object so as to become object light,  
the other split light is used as reference light, and a two-  
dimensional image formed by interference between the  
object light and reference light is captured. While changing  
the optical path length of the reference light in increments of  
 $\lambda/4$ , four two-dimensional images are obtained, which are  
then subjected to a predetermined arithmetic operation, so as  
to yield amplitude and phase images of the object.

**CITATION LIST****Patent Literature**

Patent Literature 1: Japanese Patent Publication No.  
3471556

**Non Patent Literature**

Non Patent Literature 1: F. Le Clerc, et al, "Numerical  
heterodyne holography with two-dimensional photodetector  
arrays," Optics Letters, Vol. 25, No. 10, pp. 716-718, (2000).

**SUMMARY OF INVENTION****Technical Problem**

In the observation devices using the phase shift methods  
described in Patent Literature 1 and Non Patent Literature 1,  
it is necessary for the object to stand still while obtaining four  
two-dimensional images. For obtaining a phase image of a  
moving object, it is necessary to obtain four two-dimensional  
images in a period during which the object can be presumed  
to stand still by using a two-dimensional photodetector array  
having such a high frame rate as to enable high-speed imag-  
ing. However, the photodetector capable of high-speed imag-  
ing is expensive or has such a small number of pixels that it is  
poor in spatial resolution. Its exposure time, even at the long-  
est, falls within a period during which the object can be  
presumed to stand still, so that the image quality is poor also  
in terms of SN ratio, and the sensitivity is low.

For solving the problems mentioned above, it is an object  
of the present invention to provide an observation device

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which can obtain a phase image of a moving object even when  
using a two-dimensional photodetector array having a slow  
read-out speed per pixel. For example, it is an object to pro-  
vide an observation device which can obtain a phase image of  
an object moving rapidly at a speed which is  $n$  times that of a  
two-dimensional detector having  $m \times n$  pixels in vertical and  
horizontal directions, become effective in multiple exposure  
of the object moving within a field of view, improve the SN  
ratio, and enhance the sensitivity.

**Solution to Problem**

The observation device in accordance with one aspect of  
the present invention comprises (1) a light source for irradi-  
ating a moving object with light; (2) a detection unit, letting a  
first direction be a direction on a predetermined plane yield-  
ing a fixed Doppler shift effect caused by a movement of the  
object in light having reached the predetermined plane in  
scattered light generated by the object upon irradiation with  
the light by the light source while being perpendicular to a  
moving direction of the object and a second direction be a  
direction orthogonal to the first direction on the predeter-  
mined plane while being parallel to the moving direction of  
the object, for outputting data representing a sum in the sec-  
ond direction of data temporally changing at a frequency  
corresponding to a Doppler shift frequency of the light having  
reached each position on the predetermined plane at each  
position in the first direction at each time; and (3) an arith-  
metic unit for performing a one-dimensional Fourier trans-  
form with respect to a time variable of data employing the  
position in the first direction on the predetermined plane and  
time as variables and a two-dimensional Fourier transform of  
the Fourier-transformed data, so as to yield data obtained by  
the two-dimensional Fourier transform as an image of the  
object. Here, the first direction is a direction perpendicular to  
a moving direction of the object, while the second direction is  
a direction parallel to the moving direction of the object.

In the observation device in accordance of the present  
invention, the moving object is irradiated with light by the  
light source, so as to generate scattered light. The scattered  
light incurs a Doppler shift by an amount corresponding to the  
scattering direction. The scattered light is received by the  
detection unit. In the light having reached a predetermined  
plane, a direction yielding a fixed Doppler shift effect caused  
by the movement of the object is defined as the first direction,  
and a direction orthogonal to the first direction on the prede-  
termined plane is defined as the second direction. Data rep-  
resenting a sum in the second direction of data temporally  
changing at a frequency corresponding to a Doppler shift  
frequency of the light having reached each position on the  
predetermined plane through an optical system is issued at  
each time from the detection unit at each position in the first  
direction. The arithmetic unit performs a Fourier transform  
with respect to a time variable of data employing the position  
in the first direction and time as variables and a two-dimen-  
sional Fourier transform of the Fourier-transformed data,  
whereby data obtained by the two-dimensional Fourier trans-  
form is yielded as an image of the object.

The detection unit includes (a) an optical system for receiv-  
ing a light emitted from the light source and splitting thus  
received light in two behind of the object so as to yield first  
light and second light, modulating the second light with a  
modulator, and then causing a heterodyne interference  
between the first light and the modulated second light on the  
predetermined plane; and (b) a photodetector having a light-

The arithmetic unit may comprise a first Fourier transform device for performing a one-dimensional Fourier transform with respect to the time variable and a second Fourier transform unit for performing the two-dimensional Fourier transform, while the second Fourier transform unit may comprise a third Fourier transform device for performing a one-dimensional Fourier transform with respect to a temporal frequency and a fourth Fourier transform device for performing a one-dimensional Fourier transform with respect to the first direction.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where a Fraunhofer diffraction image of the object is formed by the lens in the first direction and serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where a Fraunhofer diffraction image of the object is formed by the lens in the first direction and serving as a plane where a Fresnel diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where an image of the object is formed by the lens in the first direction and serving as a plane where a Fresnel diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence, the lens performing a one-dimensional Fourier transform with respect to the first direction.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction and serving as a plane where an image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, fourth Fourier transform device, and fourth Fourier transform device are arranged in sequence.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction and serving as a plane where a Fresnel diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, fourth Fourier transform device, and fourth Fourier transform device are arranged in sequence.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction and serving as a plane where a Fresnel diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

The observation device in accordance with another aspect of the present invention comprises a light source for irradiat-

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ing a moving object with light; a detection unit, letting a first direction be a direction on a predetermined plane yielding a fixed Doppler shift effect caused by a movement of the object in light having reached the predetermined plane in scattered light generated by the object upon irradiation with the light by the light source while being perpendicular to a moving direction of the object and a second direction be a direction orthogonal to the first direction on the predetermined plane while being parallel to the moving direction of the object, for outputting data representing a sum in the second direction of data temporally changing at a frequency corresponding to a Doppler shift frequency of the light having reached each position on the predetermined plane at each position in the first direction at each time; and an arithmetic unit for performing, for data employing a position in the first direction on the predetermined plane and time as variables, a one-dimensional Fourier transform with respect to a time variable, a one-dimensional Fourier transform with respect to the temporal frequency, and a one-dimensional Fourier transform with respect to the first direction, so as to yield data obtained by the one-dimensional Fourier transforms as an image of the object; wherein the detection unit includes an optical system for receiving a light emitted from the light source and splitting thus received light in two behind of the object so as to yield first light and second light, modulating the second light with a modulator, and then causing a heterodyne interference between the first light and the modulated second light on the predetermined plane; and a photodetector having a light receiving surface on the predetermined plane and a pixel array structure in the first direction on the light-receiving surface.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where an image of the object is formed by the lens in the first direction and serving as a plane where an image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence, the lens including an action to perform a one-dimensional Fourier transform of the diffracted light from the object 2 with respect to the first direction.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where an image of the object is formed by the lens in the first direction and serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence, the lens including an action to perform a one-dimensional Fourier transform of the diffracted light from the object 2 with respect to the first direction.

The observation device in accordance with the present invention may further comprise a lens arranged between the light source and the detection unit, the light-receiving surface of the detection unit being arranged on a plane where an image of the object is formed by the lens in the first direction and serving as a plane where a Fresnel diffraction image of the object is formed in the second direction, while the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence, the lens including an action to perform a one-dimensional Fourier transform of the diffracted light from the object 2 with respect to the first direction.

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In the observation device in accordance with the present invention, the arithmetic unit may further comprise an initial phase correction device for correcting an initial phase included in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

The observation device in accordance with the present invention may include a plurality of detection units, the arithmetic unit further comprising a summing device for yielding a sum of outputs from the plurality of detection units.

The observation device in accordance with the present invention may further comprise a converter for performing a Fourier transform or Fresnel transform with respect to the second direction.

The arithmetic unit may perform a two-dimensional Fourier transform of data in a region including a range of a Nyquist frequency in upper and lower region of a difference frequency between first and second modulation frequencies in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

The arithmetic unit may perform a one-dimensional Fourier transform with respect to the frequency and a one-dimensional Fourier transform with respect to the first direction of data in a region including a range of a Nyquist frequency in upper and lower region of a difference frequency between first and second modulation frequencies in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

The observation device in accordance with the present invention may further comprise a speed detector for detecting a moving speed of the object. In this case, during the one-dimensional Fourier transform with respect to the time variable or the two-dimensional Fourier transform, the arithmetic unit corrects a change in the speed of the object according to the speed of the object detected by the speed detector.

In the observation device in accordance with the present invention, the irradiation of the object with the light may be performed in an optical arrangement of transmitted illumination or reflected illumination. In the observation device in accordance with the present invention, the light source may be a light source for generating light in a single longitudinal mode or a light source for generating broadband light, and may be a mode-locked laser in the latter case.

#### Advantageous Effects of Invention

The present invention can obtain a phase image of a moving object even when using a photodetector having a slow read-out speed per pixel. For example, a phase image of a moving object can be obtained rapidly at a speed which is  $n$  times that of a two-dimensional detector having  $m \times n$  pixels in vertical and horizontal directions. It can also be effective in performing multiple exposure of the object moving within a field of view, thereby improving the SN ratio and enhancing the sensitivity.

#### BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a diagram for explaining a principle of acquiring a phase image of an object by the observation device in accordance with an embodiment;

FIG. 2 is a diagram for explaining a scattering direction of scattered light generated by the object;

FIG. 3 is a diagram for explaining positions at which the scattered light generated by the object reaches a back focal plane of a lens;

FIG. 4 is a diagram for further explaining the positions at which the scattered light generated by the object reaches the back focal plane of the lens;

FIG. 5 is a diagram for explaining the positions at which the scattered light generated by the object reaches the back focal plane of the lens when the object moves;

FIG. 6 is a diagram for explaining changes that occur in the optical path length until scattered light generated by the object reaches the back focal plane of the lens when the object moves;

FIG. 7 is a diagram for explaining an angle formed between a scattering direction unit vector of the scattered light generated by the object and a velocity vector of the moving object;

FIG. 8 is a diagram illustrating a structure of an observation device 1 in accordance with the embodiment;

FIG. 9 is a diagram illustrating a detailed structure of the observation device 1 in accordance with the embodiment;

FIG. 10 is a diagram illustrating a positional relationship among an object 2, a lens 40, and a photodetector 46 in the observation device 1 in accordance with the embodiment;

FIG. 11 is a diagram illustrating examples of interference images captured by the photodetector 46 when employing a first arrangement example in the observation device 1 of the embodiment;

FIG. 12 is a diagram illustrating a structural example of the lens 40 included in the observation device 1 of the embodiment;

FIG. 13 is a diagram illustrating an example of frequency distributions in interference images captured by the photodetector 46 when employing the first arrangement example in the observation device 1 of the embodiment;

FIG. 14 is a diagram schematically illustrating signals observed on a uv plane when employing the first arrangement example in the observation device 1 of the embodiment;

FIG. 15 is a diagram schematically illustrating signals observed on the uv plane when there is no frequency shift caused by modulators 20, 30 ( $\Delta f=0$ ) while employing the first arrangement example in the observation device 1 of the embodiment;

FIG. 16 is a diagram schematically illustrating an operation for obtaining a signal  $s_i(u_n, t)$  representing the sum of signals  $h_1$  to  $h_N$  on a line parallel to a v direction for each  $u_n$  when employing the first arrangement example in the observation device 1 of the embodiment;

FIG. 17 is a diagram illustrating the object 2 used in a first example;

FIG. 18 is a diagram illustrating data obtained by the first example;

FIG. 19 is a data obtained by the first example;

FIG. 20 is a diagram illustrating an initial phase  $\phi_0$  in the first example;

FIG. 21 is a block diagram illustrating structures of the photodetector 46 and an arithmetic unit 50 in the first arrangement example;

FIG. 22 is a diagram schematically illustrating signals observed on a u'v' plane when employing a second arrangement example in the observation device 1 of this embodiment;

FIG. 23 is a diagram illustrating a structural example of the lens 40 in the second arrangement example;

FIG. 24 is a block diagram illustrating structures of the lens 40, photodetector 46, and arithmetic unit 50 in the second arrangement example;

FIG. 25 is a diagram illustrating the object 2 used in a second example;

FIG. 26 is a diagram illustrating data obtained by the second example;

FIG. 27 is a diagram illustrating data obtained by the second example;

FIG. 28 is a diagram illustrating a structural example of the lens 40 in a third arrangement example;

FIG. 29 is a block diagram illustrating structures of the photodetector 46 and arithmetic unit 50 in the third arrangement example;

FIG. 30 is a schematic diagram of arithmetic operations performed by the arithmetic unit 50 in a fourth arrangement example;

FIG. 31 is a block diagram illustrating structures of the photodetector 46 and arithmetic unit 50 in the fourth arrangement example;

FIG. 32 is a schematic diagram of arithmetic operations performed by the arithmetic unit 50 in a fifth arrangement example;

FIG. 33 is a block diagram illustrating structures of the photodetector 46 and arithmetic unit 50 in the fifth arrangement example;

FIG. 34 is a schematic diagram of arithmetic operations performed by the arithmetic unit 50 in a sixth arrangement example;

FIG. 35 is a block diagram illustrating structures of the photodetector 46 and arithmetic unit 50 in the sixth arrangement example;

FIG. 36 is a diagram illustrating a structural example of the lens 40 in a seventh arrangement example;

FIG. 37 is a diagram illustrating a structural example of the lens 40 in an eighth arrangement example;

FIG. 38 is a diagram illustrating a structural example of the lens 40 in a ninth arrangement example;

FIG. 39 is a diagram illustrating a structural example of the lens 40 in a tenth arrangement example;

FIG. 40 is a diagram illustrating a structural example of the lens 40 in an eleventh arrangement example;

FIG. 41 is a diagram illustrating a structural example of the lens 40 in a twelfth arrangement example;

FIG. 42 is a diagram illustrating a structural example of the lens 40 in a thirteenth arrangement example;

FIG. 43 is a diagram illustrating a structural example of the lens 40 in a fourteenth arrangement example;

FIG. 44 is a diagram illustrating a structural example of the lens 40 in a fifteenth arrangement example;

FIG. 45 is a block diagram illustrating a schematic arithmetic device structure in the first to fifteenth arrangement examples;

FIG. 46 is a block diagram illustrating a schematic arithmetic device structure in a sixteenth arrangement example;

FIG. 47 is a block diagram illustrating a modified example of the schematic arithmetic device structure in the sixteenth arrangement example;

FIG. 48 is a block diagram illustrating a modified example of the schematic arithmetic device structure in the sixteenth arrangement example;

FIG. 49 is a block diagram illustrating a modified example of the schematic arithmetic device structure in the sixteenth arrangement example;

FIG. 50 is a block diagram illustrating a modified example of the schematic arithmetic device structure in the sixteenth arrangement example;

FIG. 51 is a graph illustrating a temporal waveform  $s^{(m)}(u, t)$  in the sixteenth arrangement example;

FIG. 52 is a graph illustrating a frequency spectrum  $S^{(m)}(u, \omega)$  in the sixteenth arrangement example;

FIG. 53 is a chart illustrating a frequency having the maximum amplitude at each position (m, n) in pseudocolor display;

FIG. 54 is a chart illustrating the amplitude and phase of a frequency spectrum  $S(u_1, \omega)$  as a result of summing signals from the pixels on a line 1;

FIG. 55 is a diagram illustrating  $G(u, 107_a)$  and complex amplitude image  $g$  in the sixteenth arrangement example;

FIG. 56 is a block diagram illustrating a modified example of the schematic arithmetic device structure in an eighteenth example;

FIG. 57 is a diagram illustrating input images in a second direction converter in the eighteenth arrangement example;

FIG. 58 is a diagram illustrating output images in the second direction converter in the eighteenth arrangement example;

FIG. 59 is a diagram illustrating data obtained by the eighteenth example;

FIG. 60 is a diagram illustrating data obtained by the eighteenth example;

FIG. 61 is a block diagram illustrating a structure in a modified example of seventeenth to nineteenth arrangement examples;

FIG. 62 is a block diagram illustrating a structure in a modified example of the seventeenth to nineteenth arrangement examples; and

FIG. 63 is a diagram illustrating a lens structure in a twentieth arrangement example.

#### DESCRIPTION OF EMBODIMENTS

In the following, modes for carrying out the present invention will be explained in detail with reference to the accompanying drawings. In the drawings, the same constituents will be referred to with the same signs while omitting their overlapping descriptions.

The observation device in accordance with an embodiment utilizes a Doppler shift effect generated when a moving object is irradiated with light, a fixed relationship between an diffraction direction of scattered light generated by the object and the Doppler shift frequency in particular, so as to acquire a phase image of the object. First, fundamental matters concerning the acquisition of the phase image of the object by the observation device in accordance with this embodiment will be explained with reference to FIGS. 1 to 7.

FIG. 1 is a diagram for explaining a principle of acquiring a phase image of an object by the observation device in accordance with this embodiment. This diagram illustrates  $\xi\eta$ ,  $xy$ , and  $uv$  coordinate systems. Each of the  $\xi$ ,  $\eta$ ,  $x$ ,  $y$ ,  $u$ , and  $v$  axes is perpendicular to the optical axis of a lens 40. The  $\xi$ ,  $x$ , and  $u$  axes are parallel to each other. The  $\eta$ ,  $y$ , and  $v$  axes are parallel to each other. An object 2 to be observed exists on the  $\xi\eta$  plane. The lens 40 exists on the  $xy$  plane. The back focal plane of the lens 40 coincides with the  $uv$  plane. The distance between the  $\xi\eta$  and  $xy$  planes is  $d$ . The distance between the  $xy$  and  $uv$  planes coincides with the focal length  $f$  of the lens 40.

The object 2 is assumed to move in the  $-\eta$  direction on the  $\xi\eta$  plane. Suppose that the object 2 is irradiated with light  $L_0$  advancing in a direction  $\zeta$  perpendicular to the  $\xi\eta$  plane. An example of the light  $L_0$  is a plane wave. Scattered light beams  $L_1$  to  $L_3$  generated by the object 2 upon irradiation with the light  $L_0$  advance in various directions and incur a Doppler shift as the object 2 moves. The scattered light  $L_1$  having a scattering direction vector component in the same direction as the moving direction of the object 2 rises in its optical frequency. The scattered light  $L_2$  having no scattering direction vector component in the moving direction of the object 2 does not change in its optical frequency. The scattered light  $L_3$  having a scattering direction vector component in a direction

opposite from the moving direction of the object 2 decreases in its optical frequency. These scattered light beams  $L_1$  to  $L_3$  reach the  $uv$  plane through the lens 40.

FIG. 2 is a diagram for explaining a scattering direction of scattered light generated by the object. For expressing the scattering direction of the scattered light generated by the object 2, it must be described by two variables, i.e., elevation angle  $\theta$  and azimuth  $\phi$ . A point source of light assumed to be arranged within the object 2 is defined as the origin of the  $\xi\eta\zeta$  coordinate system. The angle formed between the direction vector of the scattered light from the point source located at the origin and the  $\zeta$  axis is defused as the elevation angle  $\theta$ . The angle formed between a projected vector of the scattering direction vector on the  $\xi\eta$  plane and the  $\xi$  axis is defined as the azimuth  $\phi$ .

FIG. 3 is a diagram for explaining positions at which the scattered light generated by the object reaches the back focal plane of the lens. The scattered light generated when the object 2 is irradiated with the light  $L_0$  can be regarded as the secondary wave emitted from a point source assumed to be arranged within the object 2 according to Huygens' principle. In this diagram, five virtual point sources are arranged within the object 2. These point sources may exist not only on the front focal plane of the lens 40 but also in front and rear thereof.

Scattered light beams  $L_1$  to  $L_3$  having a fixed set of elevation angle  $\theta$  and azimuth  $\phi$  in the light emitted from the point sources reach one point  $P_a$  on the back focal plane of the lens 40. Scattered light beams  $L_4$  to  $L_6$  having another fixed set of elevation angle  $\theta$  and azimuth  $\phi$  in the light emitted from the point light sources reach another point  $P_b$  on the back focal plane of the lens 40. The light beams  $L_2$ ,  $L_5$  are those emitted from the point source on the front focal point of the lens 40 and thus advance in parallel with the optical axis of the lens 40 after entering the lens 40. In the light  $L_0$ , the part not scattered by the object 2 advances in parallel with the optical axis of the lens 40, so as to enter the lens 40, thereby being converged at a back focal position  $P_o$  of the lens 40.

When the object 2 moves in the  $-\eta$  direction, the optical frequencies observed at the points  $P_a$  and  $P_b$  are lower and higher than the original optical frequency  $f_0$ , respectively, under the Doppler shift effect. Since the scattering angle (elevation angle  $\theta$ , azimuth  $\phi$ ) is expanded on the back focal plane of the lens, the images on back focal of the lens plane are also referred to as angular spectrum. A light beam having a large elevation angle is converged at a position far from the center point  $P_o$  on the back focal plane of the lens. In sum, scattered light beams having the same scattering angle is converged at a single point on the back focal plane of the lens even when coming from different virtual point sources.

FIG. 4 is a diagram for further explaining the positions at which the scattered light generated by the object reaches the back focal plane of the lens. Here, scattered light beams  $L_1$  to  $L_3$  are assumed to be emitted at different scattering angles from different virtual point sources on the front focal plane of the lens in the object 2. Scattered light  $L_4$  emitted from a virtual point light source at the front focal point of the lens 40 advances in parallel with the optical axis of the lens 40 after entering the lens 40, thereby passing a point  $P_s$  on the back focal plane of the lens 40. The scattered light  $L_1$  emitted from a given virtual point source on the front focal plane of the lens 40 passes the point  $P_s$  on the back focal plane of the lens 40 when its scattering angle is the same as that of the scattered light  $L_4$  emitted from the virtual point light source at the front focal point of the lens 40. The scattered light  $L_2$  emitted from the virtual light source on the front focal point of the lens 40 has a scattering angle different from that of the scattering light

$L_4$  and thus does not pass through the point  $P_s$  while advancing in parallel with the optical axis of the lens **40** after entering the lens **40**. The scattered light  $L_3$  emitted from another virtual point source on the front focal plane of the lens **40** does not change its advancing direction before and after entering the lens **40** when assumed to pass through the center of the lens **40**. Finally, the light beams  $L_1$  to  $L_3$  are converged at a point  $P_r$  further behind the back focal plane of the lens. Scattered light beams having different scattering angles do not intersect at a single point on the back focal plane of the lens.

FIG. 5 is a diagram for explaining the positions at which the scattered light generated by the object reaches the back focal plane of the lens when the object moves. Here, objects **2a** to **2e** located to respective positions are illustrated. The objects **2a** to **2e** are assumed to include virtual point sources therein. The virtual point source in the object **2a** exists at the front focal point of the lens. The virtual point sources in the objects **2b**, **2c** are located above and below the position of the virtual point source in the object **2a**, respectively. The virtual point sources in the objects **2d**, **2e** are located in upper and lower region of the position of the virtual point source in the object **2a**, respectively. Since the objects **2a** to **2e** are irradiated with spatially uniform light  $L_0$ , scattered light beams generated at the respective point sources in the objects **2a** to **2e** have a fixed intensity distribution in an angle spectrum. That is, even when the object **2** locates at different position, the angle spectrum on the lens back focal plane yields a fixed intensity distribution.

The light changes in its phase as the object **2** locates at different position. For example, the optical path length difference between the path lengths by which the light beams  $L_{1b}$ ,  $L_{1c}$  emitted from the respective point sources in the objects **2b**, **2c** on the front focal plane of the lens reach the point  $P_a$  on the back focal plane of the lens. The optical path length by which the light  $L_{1b}$  generated by the point source in the object **2b** reaches the entrance surface of the lens **40** and the optical path length by which the light  $L_{1c}$  generated by the point light source in the object **2c** reaches the entrance surface of the lens **40** are equal to each other. However, the optical path lengths of the light beams  $L_{1b}$ ,  $L_{1c}$  from the entrance surface of the lens **40** to the point  $P_a$  differ from each other because of differences in thickness of the lens **40**. As the object **2** moves at a constant velocity, the optical path length difference changes linearly with time.

FIG. 6 is a diagram for explaining changes in optical path length by which scattered light generated by the object reaches the back focal plane of the lens when the object moves. Assumed here is a case where scattered light is observed at infinity without using the lens **40**. When the object **2** moves from the position of the object **2b** to that of the object **2c**, observing the scattered light at the point  $P_a$  on the front focal plane of the lens is equal to observing it at infinity.

When the object **2** moves in the  $-\eta$  direction on the  $\xi\eta$  plane, the amount of change  $\Delta L$  per unit time in optical path length by which the scattered light generated by the object **2** reaches a point  $P_p$  on the uv plane is represented by the following expression (1). Here,  $e_{pr}$  is the scattering direction unit vector, while  $v_p$  is the velocity vector of the object **2**. Using the amount of change  $\Delta L$  per unit time in optical path length, the phase difference, i.e., amount of change in optical frequency  $f_d$ , is represented by the following expression (2). Here,  $\lambda$  is the wavelength of light. When observing the scattered light at the position  $P_p$  on the uv plane, the optical path length of the scattered light reaching the position  $P_p$  changes as the object **2** moves, thereby varying the optical frequency. This causes the Doppler shift.

[Math. 1]

$$\Delta L = e_{pr} \cdot v_p \quad (1)$$

[Math. 2]

$$f_d = \frac{\Delta L}{\lambda} = \frac{e_{pr} \cdot v_p}{\lambda} \quad (2)$$

The Doppler shift can also be explained in terms of “time shift” which is one of properties of Fourier transforms. Let  $g(x)$  and  $G(k)$  be the complex amplitude of and Fourier transform of the object **2**, respectively. When the object **2** moves from position  $x_0$  to position  $(x_0+x)$ , the Fourier transform of the object **2** after the movement is represented by the following expression (3). The term in the exponential function in the right side of the expression (3) represents the phase. As the object **2** moves, the phase rotates in proportion to the wave number vector  $k$ , thereby causing a frequency shift. Letting  $\phi$  be the phase in the exponential function, the frequency shift  $f_d$  is represented by the following expression (4). Here,  $e_{pr}$  is the unit vector of the wave number vector  $k$ . Here,  $v_p$  represents the time derivative of the position  $x$ , i.e., the velocity of the object **2**. The expression (4) coincides with the above-mentioned frequency shift expression (2) explained from the optical path length change per unit time.

[Math. 3]

$$G'(k) = \exp(ikx)G(k) \quad (3)$$

[Math. 4]

$$f_d = \frac{1}{2\pi} \frac{\partial \phi(t)}{\partial t} = \frac{1}{2\pi} \frac{\partial (k \cdot x)}{\partial t} = \frac{e_{pr} \cdot v_p}{\lambda} \quad (4)$$

FIG. 7 is a diagram for explaining an angle formed between a scattering direction unit vector of the scattered light generated by the object and a velocity vector of the object **2**. Let  $\theta'$  be the angle formed between the projection of the scattering direction unit vector  $e_{pr}$  on the  $\eta\zeta$  plane and the  $\zeta$  axis. Here, the angle formed between the scattering direction unit vector  $e_{pr}$  and the velocity vector  $v_p$  of the object **2** is  $\theta' + \pi/2$ . Therefore, the inner product of the scattering vector and velocity vector in the right side of the expression (2) or (4) is represented by the following expression (5). Here,  $V$  is the moving speed of the object **2**. Since the numerical aperture NA of the lens **40** is defined by  $\sin\theta'$ , a Nyquist frequency  $f_{nyq}$  for obtaining a blur-free image is represented by the following expression (6).

[Math. 5]

$$f_d = \frac{e_{pr} \cdot v_p}{\lambda} = \frac{V}{\lambda} \cos(\theta' + \pi/2) = -\frac{V}{\lambda} \sin\theta' \quad (5)$$

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-continued

[Math. 6]

$$f_{Dop} = \frac{V}{\lambda} NA \quad (6)$$

Next, employing specific values, the amount of change in optical frequency  $f_d$  caused by the Doppler shift is estimated. Assuming that the object **2** is caused to flow by a commercially available flow cytometer at present, let the moving speed of the object **2** be 1 m/s. The light  $L_0$  irradiating the object **2** is assumed to be HeNe laser light having a wavelength of 633 nm. Suppose that the lens **40** has an NA of 0.45 and a magnification equivalent to 20×. When thus constructed lens **40** is used, the maximum value of the sine of the scattering angle  $\theta'$  with respect to the velocity vector  $v_p$  becomes 0.45. Therefore, the maximum Doppler shift frequency is estimated to be 710 kHz from the expression (5). When the speed is 100  $\mu$ m/s, a maximum Doppler shift frequency of 71 Hz is observed.

Through the lens **40** having a focal length  $f$ , the scattered light having the scattering angle  $\theta'$  reaches the position represented by the following expression (7) on the uv plane. Therefore, using the expressions (5) and (7) and the approximate equation of  $\tan\theta' \approx \sin\theta'$ , which holds when the angle  $\theta'$  is small, the Doppler shift frequency  $f_d$  can be expressed as a function of a v-coordinate value as in the following expression (8). It is expressed by the following expression (9) when no approximation is used.

[Math. 7]

$$v = f \tan\theta' \quad (7)$$

[Math. 8]

$$f_d = -\frac{V}{\lambda} \frac{v}{f} \quad (8)$$

[Math. 9]

$$f_d = -\frac{V}{\lambda} \sin\left(\arctan\frac{v}{f}\right) \quad (9)$$

The observation device **1** in accordance with this embodiment acquires a phase image of the object **2** according to the principle explained in the foregoing. FIG. **8** is a diagram illustrating a structure of the observation device **1** in accordance with this embodiment. The observation device **1** in accordance with this embodiment comprises a light source **10**, an illumination lens **11**, a beam splitter **12**, a first modulator **20**, a first signal generator **21**, a first amplifier **22**, a second modulator **30**, a second signal generator **31**, a second amplifier **32**, the lens **40**, a beam splitter **41**, mirrors **42**, **43**, a lens **44**, a neutral density filter **45**, a photodetector **46**, and an arithmetic unit **50**. The lens **40** is constituted by lenses **401**, **402**. FIG. **9** is a diagram illustrating the foregoing structure of the observation device **1** more specifically.

The light source **10**, an example of which is an HeNe laser light source, outputs light (optical frequency  $f_b$ ) for irradiating the object **2**. The beam splitter **12** is arranged between the lenses **401**, **402**. The beam splitter **12** receives the light emitted from the light source **10**, splits thus received light in two, and outputs the first light to the beam splitter **41** through the lens **402** and the second light to the first modulator **20**. An example of the first and second modulators **20**, **30** is an acousto-optic device. The first modulator **20** is provided with

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a first modulation signal amplified by the first amplifier **22** after being issued from the first signal generator **21**, diffracts the light emitted from the light source **10**, and outputs thus diffracted light to the second modulator **30**. The second signal modulator **30** is provided with a second modulation signal amplified by the second amplifier **32** after being issued from the second signal generator **31**, diffracts the light emitted from the first modulator **20**, and outputs thus diffracted light to the mirror **42**.

An example of the respective intensities of the first and second modulation signals fed to the first and second modulators **20**, **30** is 29 dBm. The frequencies (first and second modulation frequencies) of the first and second modulation signals slightly differ from each other. For example, the first and second modulation frequencies are 40 MHz and 40.000010 MHz, respectively, which yield a difference  $\Delta f$  of 10 Hz therebetween. Each of the first and second modulation signals is a sine wave. The first and second signal generators **21**, **31** are connected to each other by wiring in order to synchronize them.

The lens **40** receives the scattered light generated by the object **2** upon irradiation with the light from the lens **11** and forms a Fourier transform image of the object **2**. FIG. **12** illustrates the structure of the lens **40**. As illustrated in FIG. **12**, the lens **40** is constituted by the lenses **401**, **402**, between which the beam splitter **12** is arranged. Dotted lines in FIG. **12** illustrate how an image is formed.

As illustrated in FIG. **12**, a Fraunhofer diffraction image of the object is obtained on the back focal plane of the lens **401**. At the center of the Fraunhofer diffraction image of the object on the back focal plane of the lens **401**, light unaffected or less influenced by scattering appears. The light concentrating at the center of the Fraunhofer diffraction image is referred to as zero-order light. The zero-order light and the diffracted light that can be regarded as the zero-order light are light components which are unaffected or less influenced by scattering. In this specification, these light components are referred to as substantially zero-order light. The substantially zero-order light is diffracted light having such a scattering direction unit vector  $e_{pr}$  that the Doppler shift frequency  $f_d$  represented by the above-mentioned expression (2) becomes substantially 0 when the scattering direction unit vector  $e_{pr}$  and the velocity vector  $v_p$  of the object **2** are substantially orthogonal to each other.

That is, the Doppler shift frequency  $f_d$  of the substantially zero-order light having passed through the object **2** is substantially zero. The beam splitter **12**, which is arranged on the back focal plane of the lens **401**, extracts the substantially zero-order light from the light having passed through the object **2**. The beam splitter **12** splits the light issued from the lens **401** in two and outputs one of them as the first light to the lens **402**. On the other hand, as illustrated in FIG. **9**, the beam splitter **12** guides the reflected substantially zero-order light as the second light to the first modulator **20** through lenses **60**, **61**, a pinhole **62**, and a mirror **63**.

The front focal plane of the lens **60** coincides with the back focal plane of the lens **401** (uv plane). The lens **60** outputs as collimated light the substantially zero-order light issued from the beam splitter **12**. The collimated light emitted from the lens **60** has its beam diameter expanded and reduced by the lens **61**. The lens **61** represents a so-called 4f optical system constituted by two lenses, i.e., lenses **501**, **502**. The 4f optical system is an optical system in which the back focal plane of the lens **501** coincides with the front focal plane of the lens **502**, so that an image on the front focal plane of the lens **501** is formed on the back focal plane of the lens **502**.



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The pinhole **62** is arranged on the back focal plane of the lens **501**. The size of the pinhole **62** can be changed, so as to adjust the purity of a zero-order component in the substantially zero-order light extracted by the beam splitter **12**. The purity of the zero-order light component becomes higher and lower when the pinhole diameter is smaller and larger, respectively. The second light is fed into the first modulator by way of the mirror **63** after the beam diameter and the purity of the zero-order light component are adjusted by the lens **61** and the pinhole **62**.

The lens **11** collimates the light emitted from the light source **10** and irradiates the object **2** with the collimated light. The lens **44** collimates the light successively reflected by the mirrors **42**, **43** after being issued from the second modulator **30** and outputs it to the beam splitter **41**. The lens **44** is constituted by lenses **503**, **504**, which employs the structure of a 4f optical system. After being adjusted to a desirable beam diameter by the lens **44**, the light is fed to the beam splitter **41**.

The beam splitter **41** makes the respective light beams arriving from the lenses **40**, **44** incident on the light-receiving surface of the photodetector **46** and causes a heterodyne interference between the light beams on the light-receiving surface. That is, the light passing through the object **2** after being emitted from the light source **10** is received by the beam splitter **12** and split thereby in two so as to yield first light and second light, the second light is modulated by the modulators **20**, **30**, and then the beam splitter **41** causes a heterodyne interference between the first light and the modulated second light on a predetermined plane. The neutral density filter **45** is arranged in front of the light-receiving surface of the photodetector **46**. The frequency of the light incident on the light-receiving surface of the photodetector **46** after being issued from the second modulator **30** becomes  $f_b + \Delta f$ , where  $\Delta f$  is the difference frequency between the first and second modulation frequencies.

Assuming that the object **2** moves in the  $-\eta$  direction on the  $\xi\eta$  plane, the first direction yielding a fixed Doppler shift frequency concerning the movement of the object **2** in the light having reached the light-receiving surface of the photodetector **46** through the lens **40** is the  $u$  direction parallel to the  $\xi$  axis. That is, the first direction is a direction perpendicular to the moving direction of the object **2**. The second direction orthogonal to the first direction on the light-receiving surface is the  $v$  direction parallel to the  $\eta$  axis. That is, the second direction is a direction parallel to the moving direction of the object **2**. The photodetector **46** can output data representing a sum in the second direction ( $v$  direction) of data temporally changing at a frequency corresponding to a Doppler shift frequency of the light having reached each position on the light-receiving surface through the lens **40** at each position in the first direction ( $u$  direction) at each time.

The photodetector **46** preferably has a pixel array structure in the first direction ( $u$  direction), while each pixel preferably has a photosensitive region elongated in the second direction ( $v$  direction). The light-receiving surface of the photodetector **46** may be arranged on the back focal plane in the first direction of the lens **40** while coinciding with the back focal plane in the second direction of the lens **40** (a first arrangement example which will be explained later), may be an image plane (imaging plane) where an image of the object **2** is formed by the lens **40** in the first direction while coinciding with arranged on a plane where an image of the object **2** is formed in the second direction (second and fifth arrangement examples), or may be arranged on a given plane (Fresnel diffraction plane) perpendicular to the optical axis in front or

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rear of the lens **40** in each of the first and second directions (third and sixth arrangement examples).

The light-receiving surface of the photodetector **46** may be arranged on a plane where Fraunhofer diffraction images of the object are formed in the first and second directions by the lens **40** (seventh arrangement example); a plane where a Fraunhofer diffraction image of the object is formed in the first direction by the lens **40**, which is also a plane where an image of the object is formed in the second direction (eighth arrangement example); or a plane where Fraunhofer and Fresnel diffraction images of the object are formed in the first and second directions, respectively, by the lens **40** (ninth arrangement example).

The light-receiving surface of the photodetector **46** may be arranged on a plane where an image of the object is formed in the first direction by the lens **40**, which is also a plane where a Fraunhofer diffraction image of the object is formed in the second direction (tenth arrangement example); may be arranged on a plane where images of the object are formed in the first and second directions by the lens **40** (eleventh arrangement example); or maybe arranged on a plane where an image of the object is formed in the first direction by the lens **40**, which is also a plane where a Fresnel diffraction image of the object is formed in the second direction (twelfth example).

The light-receiving surface of the photodetector **46** may be arranged on a plane where Fresnel and Fraunhofer diffraction images of the object are formed in the first and second directions, respectively, by the lens **40** (thirteenth arrangement example); a plane where a Fresnel diffraction image of the object is formed in the first direction by the lens **40**, which is also a plane where an image of the object is formed in the second direction (fourteenth arrangement example); or a plane where Fresnel diffraction images of the object are formed in the first and second directions by the lens **40** (fifteenth arrangement example).

The arithmetic unit **50** performs a predetermined arithmetic operation of data, issued from the photodetector **46**, employing the position in the first direction ( $u$  direction) on the light-receiving surface and time as variables, so as to obtain an image of the object **2**. For carrying out this operation, the arithmetic unit **50** comprises a first Fourier transform device **51** for performing a one-dimensional Fourier transform with respect to a time variable and a second Fourier transform unit **52** for performing a two-dimensional Fourier transform. The second Fourier transform unit **52** comprises a third Fourier transform device **53** for performing a one-dimensional Fourier transform with respect to the frequency and a fourth Fourier transform device **54** for performing a one-dimensional Fourier transform with respect to the first direction. Details of the arithmetic operation will be explained later.

FIG. **10** is a diagram illustrating a positional relationship among the object **2**, lens **40**, and photodetector **46** in the observation device **1** in accordance with this embodiment. In this diagram, parts (a) and (b) are views seen in the  $\eta$  and  $\xi$  directions, respectively. The diagram illustrates a  $\xi\eta$  coordinate system having an origin at the front focal point of the lens **40**, an  $xy$  coordinate system having an origin at the center of the lens **40**, a  $uv$  coordinate system having an origin at the back focal point of the lens **40**, a  $u'v'$  coordinate system having an origin at the imaging plane center position produced by the lens **40**, and a  $u''v''$  coordinate system having an origin at a given position on the optical axis of the lens **40**. The light-receiving surface of the photodetector **46** coincides with the  $uv$ ,  $u'v'$ , and  $u''v''$  planes in the first, second, and third arrangement examples, respectively.

As illustrated in part (b) of the diagram, light beams  $L_4$  to  $L_6$  generated at the same angle in virtual point sources  $g_1$  to  $g_3$  in the object **2** intersect at one point  $a$  on the  $uv$  plane, which is the back focal plane of the lens, and then diverge, so as to reach points  $h$ ,  $g$ , and  $f$  on the  $u'v'$  plane, which is the imaging plane of the lens. The light beams  $L_4$  to  $L_6$  have the same scattering angle  $\theta'$  and thus incur the same frequency shift by Doppler effect.

A difference between respective signals received by the photodetector **46** in the first and second arrangement examples will now be explained. In the first arrangement example, a frequency shift is observed with regularity in the  $v$  direction, while a one-to-one relationship exists between the position in the  $v$  direction and the frequency shift amount. In the second arrangement example, on the other hand, no frequency shift is arranged with regularity in the  $v'$  direction, and no one-to-one relationship exists between the position in the  $v'$  direction and the frequency shift amount.

For placing irregularly arranged frequency shift in the  $v'$  direction in order (i.e., in such an order that they are observed on the light-receiving surface of the photodetector **46** in the first arrangement example) in the second arrangement example, a Fourier transform is performed after combining (summing) the waveforms observed at the points  $f$ ,  $g$ , and  $h$  on the  $u'v'$  plane; this makes their frequency linear (regular), while yielding their amplitude and phase.

This is equivalent to the fact that the amplitude and phase at each frequency are obtained by a Fourier transform after summing waveforms  $h_1$ ,  $h_2$ , and  $h_3$  in the  $v$  direction as illustrated in the graph in FIG. **13** in the first arrangement example in which frequency shifts are arranged with regularity in the  $v$  direction on the light-receiving surface of the photodetector **46** as well. In other words, as long as the photodetector **46** has a light-receiving surface in such a size as to cover the scattered light incurring a Doppler shift caused by the object **2**, there are no changes in obtained signals regardless of where the photodetector **46** receives light, and the distribution obtained on the light-receiving surface of the photodetector **46** in the first arrangement example can be restored since it is encoded with the frequency.

On the other hand, as illustrated in part (a) of FIG. **10**, no Doppler shift is incurred with respect to the  $u$  direction, so that the distribution cannot be restored by arithmetic operations and the like even when signals are integrated in the  $u$  direction. Because of the foregoing, the photodetector **46** is required to have a pixel array structure in the  $u$  direction but not in the  $v$  direction.

FIG. **11** is a examples of interference images captured by the photodetector **46** when employing the first arrangement example in the observation device **1** of this embodiment. Here, the object **2**, for which one having a circular aperture with a diameter of  $50\text{ }\mu\text{m}$  was employed, was moved at a velocity of  $30\text{ }\mu\text{m/s}$ . The light-receiving surface of the photodetector **46**, for which a two-dimensional CCD camera was used, was arranged on the back focal plane of the lens **40**. As the lens **40**, one having a structure including an objective lens **401** (having a magnification of  $20\times$ ) and a relay lens **402** (having a focal length of  $30\text{ mm}$ ) as illustrated in FIG. **12** was used, while an image on the back focal plane located within the objective lens **401** was formed on the light-receiving surface of the photodetector **46** by the relay lens **402**.

Parts (a) to (i) in FIG. **11** illustrate respective interference images captured at intervals of  $1\text{ sec}$  in sequence. As can be seen from the images, a diffraction pattern (so-called airy disk pattern) caused by the circular aperture does not change, though interference fringes vary as time passes. This phenomenon empirically shows that only the phase changes

while the intensity distribution of angular spectrum of scattered light reaching the back focal plane of the lens is constant even when the object **2** moves in the  $-\eta$  direction on the  $\xi\eta$  plane as explained with reference to FIG. **5**.

FIG. **13** is an example of frequency distributions in interference images captured by the photodetector **46** when employing the first arrangement example in the observation device **1** of the embodiment. Here, the object **2**, for which one having a circular aperture with a diameter of  $200\text{ }\mu\text{m}$  was employed, was moved at a velocity of  $100\text{ }\mu\text{m/s}$ . The light-receiving surface of the photodetector **46**, for which a two-dimensional CCD camera was used, was arranged on the back focal plane of the lens **40**. As the lens **40**, one constructed as illustrated in FIG. **12** (but with a different magnification) was used. As illustrated in FIG. **13**, the frequency changes along the  $v$  direction (second direction) from  $10\text{ Hz}$  as a center, which is the difference frequency  $\Delta f$  between the first and second modulation frequencies. This is the Doppler shift frequency itself. On the other hand, a frequency is fixed along the  $u$  direction (first direction).

Details of arithmetic operations in the arithmetic unit **50** in the respective cases employing the first to fifteenth arrangement examples in the observation device **1** in accordance with this embodiment will now be explained.

#### First Arrangement Example

In the first arrangement example, the light-receiving surface of the photodetector **46** is arranged on the back focal plane in the first direction of the lens **40**, which is also the back focal plane ( $uv$  plane) in the second direction of the lens **40**. Here, the Fourier transform image on the  $uv$  plane of an complex amplitude image  $g(\xi, \eta)$  of the object **2** on the plane  $\xi\eta$  plane by the lens **40** is represented by the following expression (10). The expression (10) includes a term of a Fourier transform image  $G(u, v)$  of the object **2** and completely coincides with  $G(u, v)$  under the condition where  $d=f$ .

[Math. 10]

$$G''(u, v) = \frac{A \exp \left[ j \frac{k}{2f} \left( 1 - \frac{d}{f} \right) (u^2 + v^2) \right]}{j \lambda f} \int \int g(\xi, \eta) \exp \left[ -j \frac{2\pi}{\lambda f} (\xi u + \eta v) \right] d\xi d\eta \quad (10)$$

In the structure of the observation device **1**, the scattered light (having an optical frequency of  $f_b - f_d$ ) transmitted through the lens **40** after having received a Doppler shift from the object **2** and the reference light (having an optical frequency of  $f_b + \Delta f$ ) whose frequency is shifted by  $\Delta f$  from the optical frequency  $f_b$  by the first and second modulators **20**, **30** reach the  $uv$  plane (the light-receiving surface of the photodetector **46**), which is the back focal plane of the lens **40**, through the beam splitter **41**. Because of a heterodyne interference between these light beams on the  $uv$  plane, a beat signal having the difference frequency  $(\Delta f + f_d)$  between the respective optical frequencies of the scattered light and reference light is observed at each position on the  $uv$  plane. The optical frequency change amount  $f_d$  of the scattered light caused by the Doppler shift can be expressed as a function of the  $v$ -coordinate value as in the above-mentioned expression (8).

FIG. **14** is a diagram schematically illustrating signals observed on the  $uv$  plane when employing the first arrangement example in the observation device **1** of this embodiment. This diagram schematically illustrates temporal waveforms of respective signals at positions  $v_1$ ,  $v_2$ ,  $v_3$  on a line parallel to

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the  $v$  direction with respect to  $u_n$  ( $n=1$  to  $N$ ) on the  $uv$  plane. Since the object **2** moves in the  $-\eta$  direction on the  $\xi\eta$  plane, a signal  $h_1$  having a frequency  $(\Delta f - |f_d|)$  lower than  $\Delta f$  is obtained at a position  $(u_n, v_1)$  where the  $v$ -coordinate value  $v_1$  is positive on the  $uv$  plane. A signal  $h_2$  having a frequency  $\Delta f$  is obtained at a position  $(u_n, v_2)$  where the  $v$ -coordinate value  $v_2$  is 0 on the  $uv$  plane. A signal  $h_3$  having a frequency  $(\Delta f + |f_d|)$  higher than  $\Delta f$  is obtained at a position  $(u_n, v_3)$  where the  $v$ -coordinate value  $v_3$  is negative on the  $uv$  plane.

For an example, FIG. 15 schematically illustrates signals observed on the  $uv$  plane when there is no frequency shift caused by the modulators **20**, **30** ( $\Delta f=0$ ) while employing the first arrangement example in the observation device **1** of this embodiment. In this case, a DC signal  $h_3$  is obtained at a position  $(u_n, v_3)$  where the  $v$ -coordinate value  $v_3$  is 0 on the  $uv$  plane. Two positions  $(u_n, v_1)$ ,  $(u_n, v_5)$  whose  $v$ -coordinate values have the same absolute value with different signs (positive or negative) on the  $uv$  plane yield respective signals  $h_1$ ,  $h_5$  having the same frequency with phases differing from each other by  $\pi$ . Similarly, two positions  $(u_n, v_2)$ ,  $(u_n, v_4)$  whose  $v$ -coordinate values have the same absolute value with different signs (positive or negative) on the  $uv$  plane yield respective signals  $h_2$ ,  $h_4$  having the same frequency with phases differing from each other by  $\pi$ .

When the first arrangement example is employed in the observation device **1** of this embodiment, the signal  $h_n$  observed at a position  $(u_n, v)$  on the  $uv$  plane, which is the back focal plane of the lens, has a frequency  $\Delta f + f_d = \Delta f(V/\lambda f)$   $v$ . That is, the signal  $h_n$  observed at the position  $(u_n, v)$  varies depending on the  $v$ -coordinate value. The  $v$ -coordinate value and the frequency are related to each other. Therefore, when a signal  $s_1(u_n, t)$  representing the sum of signals  $h_1$  to  $h_N$  on a line parallel to the  $v$  direction is obtained for given  $u_n$ , the signal (amplitude, phase) at each position  $(u_n, v)$  can be specified by analyzing the frequency of the signal  $s_1(u_n, t)$ .

FIG. 16 is a diagram schematically illustrating an operation for obtaining the signal  $s_1(u_n, t)$  representing the sum of signals  $h_1$  to  $h_N$  on a line parallel to the  $v$  direction for each  $u_n$  when employing the first arrangement example in the observation device **1** of this embodiment. In this diagram,  $\Sigma$  represents an arithmetic operation for the sum of signals  $h_1$  to  $h_N$ . The signal  $s_1(u, t)$  indicating the sum of signals  $h(v)$  on a line parallel to the  $v$  direction with respect to a given  $u$ -coordinate value is represented by the following expression (11). Here,  $G(u, v)$  is a Fourier transform image (complex amplitude) of the object **2** obtained on the  $uv$  plane. Sign  $\angle$  represents the phase of the complex amplitude. Here,  $\phi_0$  indicates the initial phase resulting from optical conditions of scattered light and reference light.  $A_0$  represents the distribution in intensity of scattered light and reference light. Here,  $t$  is a time variable. The term of DC components is omitted.

[Math. 11]

$$s_1(u, t) = \int h(v) dv \quad (11)$$

$$= \int A_0(u, v) |G(u, v)| \cos \left( \frac{2\pi(\Delta f + f_d)t + \angle G(u, v) + \phi_0(u, v)}{\lambda f} \right) dv$$

As the photodetector **46**, one having a pixel array structure in which pixels  $e_1$  to  $e_n$  are arranged in the  $u$  direction, while the pixel  $e_n$  corresponding to each  $u_n$  has a photosensitive region elongated in the  $v$  direction, is favorably used as mentioned above. The signal issued from the pixel  $e_n$  in the pixel

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array structure corresponds to the signal  $s_1(u_n, t)$  represented by the above-mentioned expression (11).

The above-mentioned expression (11) is represented in complex notation by the following expression (12). Here,  $\Delta\omega$  indicates  $\Delta f$  in terms of angular frequency, and  $\Delta\omega = 2\pi\Delta f$ . Here,  $\omega_d$  indicates  $f_d$  in terms of angular frequency, and  $\omega_d = 2\pi f_d$ . Here,  $v = a\omega_d$ , and  $a = \lambda f / (2\pi V)$ .  $A_0$  and  $\phi_0$  are omitted in the expression (12).  $A_0$  and  $\phi_0$  will also be omitted in the following mathematical expressions.

[Math. 12]

$$s_1(u, t) = a \exp(i\Delta\omega t) \int G(u, a\omega) \exp(i\omega_d t) d\omega_d \quad (12)$$

In the right side of the expression (12), the exponential function  $\exp(i\Delta\omega t)$  in front of the integral sign means that the function subsequent thereto is modulated by the frequency  $\Delta\omega$ . Specifically, it means that a frequency shift occurs by the frequency  $\Delta\omega$  in the frequency region. This frequency shift can empirically be confirmed by the fact that a frequency shift to a frequency of 10 Hz occurs as illustrated in parts (b) and (c) of FIG. 18. The integral sign in the expression (12) indicates an inverse Fourier transform of the complex amplitude  $G(u, v)$  with respect to the variable  $v$  or  $\omega_d$ .

A one-dimensional Fourier transform of the signal  $s_1(u, t)$  with respect to the time variable  $t$  is represented by the following expression (13). The rightmost side of the expression (13) indicates a signal of  $G(u, v)$ , which is a two-dimensional Fourier transform image of the complex amplitude image  $g(\xi, \eta)$  of the object **2**, shifted by a frequency of  $\Delta v = a\Delta\omega$ .

[Math. 13]

$$\int s_1(u, t) \exp(-i\omega t) dt = a G(u, a(\Delta\omega + \omega)) = a G(u, \Delta v + v) \quad (13)$$

An example (first example) in the first arrangement example will now be explained. As the photodetector **46**, a digital CCD camera having 640×480 pixels, capable of capturing images at 30 frames/s, was used in the first example. Using this photodetector **46**, images were captured at fixed time intervals, and image data captured at each time were fed into a personal computer (PC). An arithmetic operation by the PC determined the sum of the signals issued from the each pixel on a line parallel to the  $v$  direction with respect to a given  $u$ -coordinate value, thereby yielding data of the signal  $s_1(u, t)$ .

FIG. 17 is a diagram illustrating the object **2** used in the first example. The object **2** used in the first example is one in which chromium was vapor-deposited on a transparent glass sheet having a thickness of about 1.5 mm, so as to draw the depicted pattern. Black regions in the diagram are light-transmitting regions, while the white region is a light-shielding region where chromium was vapor-deposited. The object **2** was moved in the direction of the depicted arrow at a speed of 100  $\mu\text{m/s}$  by a motorized actuator (LTA-HS manufactured by Newport Corporation).

FIG. 18 is a diagram illustrating data obtained by the first example. Part (a) of the diagram, whose horizontal and vertical axis indicate the time variable  $t$  and variable  $u$ , respectively, illustrates data of the signal  $s_1(u, t)$ . Part (b) of the diagram, whose horizontal and vertical axis indicate the frequency and the variable  $u$ , respectively, illustrates the amplitude of data obtained by a one-dimensional Fourier transform with respect to the time variable  $t$  of the data of the signal  $s_1(u, t)$  in the part (a) of the diagram. Part (c) of the diagram, whose horizontal and vertical axis indicate the frequency and the variable  $u$ , respectively, illustrates the phase of the data obtained by the one-dimensional Fourier transform with respect to the time variable  $t$  of the data of the signal  $s_1(u, t)$  in the part (a) of the diagram.

The parts (b) and (c) in the diagram are obtained by the one-dimensional Fourier transform (the above-mentioned

expression (13)) with respect to the time variable  $t$  of the data of the signal  $s_1(u, t)$  illustrated in the part (a) of the diagram. In this example, the difference  $M$  between the first and second modulation frequencies is 10 Hz, whereby it is seen in the parts (b) and (c) of the diagram that the Fourier transform image  $G(u, v)$  is obtained about the difference signal  $\Delta f=10$  Hz acting as the center. This is caused by the modulation term  $\exp(i\Delta\omega t)$  in the above-mentioned expression (12).

FIG. 19 is also a diagram illustrating data obtained by the first example. FIG. 19(a) illustrates amplitude data cutting out a fixed area centered at the difference signal  $\Delta f=10$  Hz from the phase data of FIG. 18(b). FIG. 19(b) illustrates phase data cutting out a fixed area centered at the difference signal  $\Delta f=10$  Hz from the amplitude data of FIG. 18(c). The fixed area cut out here is a region including the range of a Nyquist frequency  $f_{nyq}$  represented by the above-mentioned expression (6) in upper and lower region of the difference frequency  $\Delta f$ . This cutting operation yields the  $G(u, v)$  represented in the following expression (14). The phase data in FIG. 19(b) are those obtained after calibration with the initial phase  $\phi_0$  illustrated in FIG. 20. This calibration does not affect the amplitude data in FIG. 19(a).

[Math. 14]

$$G(u, \Delta\omega + \omega_d) \Rightarrow G(u, \omega_d) \quad (14)$$

FIG. 19(c) illustrates the amplitude of data obtained by a two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. 19. FIG. 19(d) illustrates the phase of the data obtained by the two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. 19. As illustrated by the following expression (15), the parts (c) and (d) in FIG. 19 represent the complex amplitude image  $g(\xi, \eta)$  of the object 2 obtained by the two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. 19.

[Math. 15]

$$\iint G(u, \omega_d) \exp(i(u\xi + v\eta)) du dv = g(\xi, \eta) \quad (15)$$

In the first arrangement example in which the light-receiving surface of the photodetector 46 is arranged on the back focal plane in the first direction of the lens 40, which is also the back focal plane (uv plane) in the second direction of the lens 40 in the structure of the observation device 1 in accordance with this embodiment, the arithmetic unit 50 performs the foregoing arithmetic processing, so as to obtain the image of the object 2. That is, the arithmetic unit 50 acquires data of the signal  $s_1(u, t)$  employing the position  $u$  on the uv plane and the time  $t$  as variables, performs a one-dimensional Fourier transform of the data of the signal  $s_1(u, t)$  with respect to the time variable  $t$  (the above-mentioned expression (13)), cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from the data obtained by the one-dimensional Fourier transform (the above-mentioned expression (14)), and performs a two-dimensional Fourier transform of thus cut-out data (the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object 2.

FIG. 21 is a diagram illustrating structures of the photodetector 46 and arithmetic unit 50 in the first arrangement example performing the foregoing arithmetic processing. The arithmetic unit 50 comprises a first Fourier transform device 51, a second Fourier transform unit 52, and a specific region cutting device 55. The second Fourier transform unit 52 includes a third Fourier transform device 53 and a fourth Fourier transform device 54. The first Fourier transform device 51 performs a one-dimensional Fourier transform of

data of the signal  $s_1(u, t)$  employing the position  $u$  on the uv plane and the time  $t$  as variables with respect to the time variable  $t$  (Fourier transform with respect to the time in the above-mentioned expression (13)). The specific region cutting device 55 cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from the data  $G$  obtained by the one-dimensional Fourier transform (the above-mentioned expression (14)). The third Fourier transform device 53 performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega_d$  in the above-mentioned expression (15)). The fourth Fourier transform device 54 performs a Fourier transform with respect to the variable  $u$  (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the first Fourier transform device 51, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order in the arithmetic unit 50 in the first arrangement example. The fourth Fourier transform device 54 is not restricted to the position mentioned above but may be arranged between the first and third Fourier transform devices 51, 53, or in front of the first Fourier transform device 51, for example. Using such arithmetic unit 50, the signal  $s_1(u, t)$  is subjected to arithmetic operations, whereby the image  $g(\xi, \eta)$  of the object 2 is obtained.

In the first arrangement example, the light-receiving surface of the photodetector 46 is only required to be arranged on a plane equivalent to the back focal plane of the lens 40 and thus may be arranged on a plane within a region which is sufficiently far from the object 2 so that Fraunhofer diffraction can occur.

In the foregoing first arrangement example, a two-dimensional CCD camera is used as the photodetector 46. For obtaining data of the signal  $s_1(u, t)$ , the photodetector 46 may have a one-dimensional pixel array structure instead of the two-dimensional pixel array structure. Therefore, the observation device 1 of this embodiment can obtain a phase image of the moving object 2 even when using the photodetector 46 having a one-dimensional pixel array structure and exhibiting a slow read-out speed per pixel.

For example, it can obtain a phase image of an object moving rapidly at a speed which is  $n$  times that of a two-dimensional detector having  $m \times n$  pixels in vertical and horizontal directions. It can also be effective in multiple exposure of the object moving within a field of view, thereby improving the SN ratio and enhancing the sensitivity. Cameras (e.g., vision chips and profile sensors) equipped with in-chip arithmetic functions which can directly calculate a modulation frequency of detected light can also be utilized as the photodetector 46. Here, an image corresponding to the modulation frequency can be obtained directly, whereby the image illustrated in FIG. 1 can be displayed in real time. Further, the above-mentioned cameras equipped with the in-chip arithmetic functions can directly output a reconstructed speed image from the detector.

#### Second Arrangement Example

The second arrangement example will now be explained. In the second arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where an image of the object 2 is formed in the first direction by the lens 40, which is also a plane (u'v' plane) where an image of the object 2 is formed in the second direction by the lens 40. As illustrated in FIG. 10, light beams  $L_1$  to  $L_4$  reaching a point  $h$  on the imaging plane (u'v' plane) caused by the lens 40 are emitted from a common virtual point source  $g_1$  within the

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object 2. These light beams  $L_1$  to  $L_4$  are emitted from the virtual point source  $g_1$  at scattering angles  $\theta'$  different from each other and thus yield Doppler shift frequencies  $f_d$  different from each other.

FIG. 22 is a diagram schematically illustrating signals observed on the  $u'v'$  plane when employing the second arrangement example in the observation device 1 of this embodiment. In the second arrangement example, scattered light beams having various frequencies are incident on the  $u'v'$  plane at each point. Therefore, as illustrated in the left side of the diagram, a beat signal  $h(u', v')$  obtained by a heterodyne interference between scattered light and reference light at each point on the  $u'v'$  plane includes various frequency components. Let  $h_{10}$ ,  $h_{11}$ , and  $h_{12}$  be respective signals observed at positions  $(u'_n, v'_1)$ ,  $(u'_n, v'_2)$ , and  $(u'_n, v'_3)$  on the  $u'v'$  plane. Let  $s_2(u'_n, t)$  be a signal representing the sum of signals  $h_{10}$  to  $h_{12}$  on a line parallel to the  $v'$  direction with respect to given  $u'_n$  (in the center of the diagram).

As illustrated in the right side of the diagram, a one-dimensional Fourier transform of the signal  $s_2(u'_n, t)$  with respect to the time variable  $t$  yields a frequency distribution similar to that along the  $v$  direction on back focal plane of the lens ( $uv$  plane) in the first arrangement example. That is, the one-dimensional Fourier transform of the signal  $s_2(u'_n, t)$  with respect to the time variable  $t$  converts an irregular frequency distribution on the  $u'v'$  plane (on the left in the diagram) into a regular frequency distribution (on the right in the diagram). Since the light-receiving surface of the photodetector 46 is arranged on the imaging plane ( $u'v'$  plane) caused by the lens 40, a Fourier transform of the signal  $s_2(u'_n, t)$  with respect to the variable  $u'$  can yield the same distribution as that on the  $uv$  plane. More specifically concerning the  $u'$  direction, an optical Fourier transform by a lens 404 in FIG. 23 and an inverse Fourier transform by the arithmetic unit 50 carry out no Fourier transform in the  $u'$  direction, whereby a distribution with respect to the  $u$  direction in the first arrangement example is obtained.

That is, a two-dimensional Fourier transform image  $G(u, \Delta v + v)$  for a complex amplitude image  $g(\xi, \eta)$  of the object 2 can be obtained by the following expression (16). This Fourier transform image  $G(u, \Delta v + v)$  is equivalent to that in the first arrangement example, whereby subsequent arithmetic processing similar to that in the first arrangement example can yield the complex amplitude image  $g(\xi, \eta)$  of the object 2.

[Math. 16]

$$\iint s_2(u', t) \exp(i(u'u + \omega t)) du' dt = G(u, \Delta \omega + \omega_d) \quad (16)$$

In the second arrangement example in which the light-receiving surface of the photodetector 46 is arranged on a plane where an image of the object 2 is formed in the first direction by the lens 40, which is also a plane ( $u'v'$  plane) where an image of the object 2 is formed in the second direction in the structure of the observation device 1 in accordance with this embodiment, the arithmetic unit 50 performs the foregoing arithmetic processing, so as to obtain the image of the object 2. That is, the arithmetic unit 50 acquires data of the signal  $s_2(u', t)$  employing the position  $u'$  on the  $u'v'$  plane and the time  $t$  as variables, performs a Fourier transform of the data of the signal  $s_2(u', t)$  with respect to the variable  $u'$  and the time variable  $t$  (the above-mentioned expression (16)), cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from the data  $G$  obtained by the Fourier transform (the above-mentioned expression (14)), and performs a two-dimensional Fourier transform of thus cut-out data (the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object 2.

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FIG. 24 is a diagram illustrating structures of the lens 40, photodetector 46, and arithmetic unit 50 in the second arrangement example performing the foregoing arithmetic processing. The arithmetic unit 50 comprises a first Fourier transform device 51, a second Fourier transform unit 52, and a specific region cutting device 55. The second Fourier transform unit 52 includes a third Fourier transform device 53 and a fourth Fourier transform device 54. The first Fourier transform device 51 performs a Fourier transform of data of the signal  $s_2(u', t)$  employing the position  $u'$  on the  $u'v'$  plane and the time  $t$  as variables, optically Fourier-transformed by the lens 40, with respect to the time variable  $t$  (Fourier transform with respect to the time variable  $t$  in the above-mentioned expression (16)). The fourth Fourier transform device 54 arranged behind the first Fourier transform device 51 performs a Fourier transform of the data obtained by the preceding Fourier transform with respect to the variable  $u'$  (Fourier transform with respect to the variable  $u'$  in the above-mentioned expression (16)). The specific region cutting device 55 cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from the data  $G$  obtained by this Fourier transform (the above-mentioned expression (14)). The third Fourier transform device 53 performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega_d$  in the above-mentioned expression (15)). The fourth Fourier transform device 54 arranged behind the third Fourier transform device 53 performs a Fourier transform with respect to the variable  $u$  (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the first Fourier transform device 51, fourth Fourier transform device 54, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order in the arithmetic unit 50 in the second arrangement example. The fourth Fourier transform device 54 arranged behind the first Fourier transform device 51 is not restricted to this position but may be arranged between the third Fourier transform device 53 and the fourth Fourier transform device 54 arranged behind the third Fourier transform device 53, or in front of the first Fourier transform device 51, for example. The fourth Fourier transform device 54 arranged behind the third Fourier transform device 53 is not restricted to this position but may be arranged between the fourth Fourier transform device 54 arranged behind the first Fourier transform device 51 and the third Fourier transform device 53, or in front of the first Fourier transform device 51, for example. Using such arithmetic unit 50, the signal  $s_2(u', t)$  is subjected to arithmetic operations, whereby the image  $g(\xi, \eta)$  of the object 2 is obtained.

An example (second example) in the second arrangement example will now be explained. In the second example, as the lens 40, one having a structure including an objective lens 403 (having a focal length  $f_1$ ) and a lens 404 (whose focal length  $f_2 = 50$  mm) as illustrated in FIG. 23 was used, while an image of the object 2 was formed on the light-receiving surface of the photodetector 46 by these two lenses 403, 404. As illustrated in FIG. 23, the beam splitter 12 was arranged between the lenses 403, 404. The beam splitter 12 was arranged on the back focal plane of the lens 403 constituting the lens 40 such as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 was fed to the lens 60 as the second light.

FIG. 25 is a diagram illustrating the object 2 used in the second example. The object 2 used in the second example was one in which the depicted pattern was drawn on a flat sheet

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made of PMMA. Depicted black regions were formed as depressions having a thickness of  $633 \text{ nm} \pm 25 \text{ nm}$  with respect to white regions. The size of the object **2** shown in FIG. **25** is  $5 \text{ mm (L)} \times 5 \text{ mm (W)}$ . The other conditions are the same as those in the first example.

FIG. **26** is a diagram illustrating data obtained by the second example. Part (a) of the diagram, whose horizontal axis and vertical axis indicate the time variable  $t$  and variable  $u'$ , respectively, illustrates data of the signal  $s_2(u', t)$ . Part (b) of the diagram, whose horizontal axis and vertical axis indicate the frequency and the variable  $u$ , respectively, illustrates the amplitude of data obtained by a Fourier transform with respect to the variable  $u'$  and time variable  $t$  of the data of the signal  $s_2(u', t)$  in the part (a) of the diagram. Part (c) of the diagram, whose horizontal axis and vertical axis indicate the frequency and the variable  $u$ , respectively, illustrates the phase of the data obtained by the Fourier transform with respect to the variable  $u'$  and time variable  $t$  of the data of the signal  $s_2(u', t)$  in the part (a) of the diagram.

The parts (b) and (c) in the diagram were obtained by the Fourier transform (the above-mentioned expression (16)) with respect to the variable  $u'$  and time variable  $t$  of the data of the signal  $s_2(u', t)$  illustrated in the part (a) of the diagram. In this example, the difference  $\Delta f$  between the first and second modulation frequencies was also  $10 \text{ Hz}$ , whereby it is seen in the parts (b) and (c) of the diagram that the Fourier transform image  $G(u, v)$  was obtained about the difference signal  $\Delta f = 10 \text{ Hz}$  acting as the center.

FIG. **27** is also a diagram illustrating data obtained by the second example. FIG. **27(a)** illustrates amplitude data cutting out a fixed area centered at the difference signal  $\Delta f = 10 \text{ Hz}$  from the amplitude data of FIG. **26(b)**. FIG. **27(b)** illustrates phase data cutting out a fixed area centered at the difference signal  $\Delta f = 10 \text{ Hz}$  from the phase data of FIG. **26(c)**. The fixed area cut out here is a region including the range of a Nyquist frequency  $f_{\text{nyq}}$  represented by the above-mentioned expression (6) in upper and lower region of the difference frequency  $\Delta f$ .

The phase data in FIG. **27(b)** are those calibrated with (subtracting) the initial phase  $\phi'_0$ . In the second arrangement example, the  $u'$  direction of  $s_2(u', t)$  is an imaging direction, whereby the initial phase may be zero or a uniform distribution in the  $u'$  direction. In the  $v'$  direction, on the other hand, the data are calibrated with the initial phase under optical conditions of reference light and scattered light.

FIG. **27(c)** illustrates the amplitude of data obtained by a two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. **27**. FIG. **27(d)** illustrates the phase of the data obtained by the two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. **27**. The parts (c) and (d) in FIG. **27** represent the complex amplitude image  $g(\xi, \eta)$  of the object **2** obtained by the two-dimensional Fourier transform of the complex amplitude image  $G(u, v)$  represented by the parts (a) and (b) of FIG. **27**.

#### Third Arrangement Example

The third arrangement example will now be explained. The third arrangement example uses the lens structure illustrated in FIG. **28**. In the third arrangement example, as illustrated in FIG. **28**, the beam splitter **12** is arranged on the back focal plane of a lens **405** so as to split the substantially zero-order light in two. The light reflected by the beam splitter **12** is fed to the lens **60** as the second light. In the third arrangement example, the light-receiving surface of the photodetector **46** is arranged on a  $u''v''$  plane which is a given plane perpendicular to the optical axis in front or rear of the lens **40** in both of the first and second directions. The  $u''v''$  plane is treated as a

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Fresnel diffraction plane. A Fresnel diffraction image  $g''(u'', v'')$  of the complex amplitude image  $g(\xi, \eta)$  of the object **2** is represented by the following expression (17). The following expression (18) represents  $h$  in the expression (17).  $H$  is a Fourier transform of  $h$ .  $G$  is a Fourier transform of the complex amplitude image  $g(\xi, \eta)$  of the object **2**.  $FT^{-1}$  is a sign representing an arithmetic operation of a two-dimensional inverse Fourier transform. The variable  $z$  in the expression is the gap (distance) between the  $\xi\eta$  and  $u''v''$  planes. Here,  $k$  is the wave number, and  $\lambda$  is the wavelength.

[Math. 17]

$$g''(u'', v'') = \iint g(\xi, \eta) h(u'' - \xi, v'' - \eta) d\xi d\eta \quad (17)$$

$$= FT^{-1}[G \cdot H]$$

[Math. 18]

$$h(u, v) = \frac{e^{ikz}}{i\lambda z} \exp\left[\frac{ik}{2z}(u^2 + v^2)\right] \quad (18)$$

The expression (17) means that an inverse Fourier transform of the product of  $G(u, v)$  on the  $uv$  plane and  $H(u, v)$ , equivalent to the image  $g''(u'', v'')$ , appears on the  $u''v''$  plane. In other words, the expression (17) means that a Fourier transform of the image  $g''(u'', v'')$  appearing on the  $u''v''$  plane yields the product of  $G$  and  $H$ .

Therefore, letting  $s_3(u'', t)$  be a signal representing the sum of signals on a line parallel to the  $v''$  direction with respect to given  $u''$  on the  $u''v''$  plane, a Fourier transform of data of the signal  $s_3(u'', t)$  with respect to the variable  $u''$  and time variable  $t$  yields the product of  $G(u, v)$  on the  $uv$  plane and  $H(u)$  as illustrated in the following expression (19).

Here,  $H(u)$  represents a function which is uniform in the  $v$  direction in functions  $H$  obtained by a two-dimensional Fourier transform of the expression (18). More specifically concerning the  $u''$  direction, the Fourier transform with respect to the variable  $u''$  by the arithmetic unit **50** has the same effect as that of the optical Fourier transform arranging the lens **40** in FIG. **1**, thereby yielding a distribution represented by  $d\omega$  in the expression (10). In the  $v''$  direction, on the other hand, the same distribution as with  $v$  in the first arrangement example is obtained because of the reason mentioned above.

[Math. 19]

$$\iint s_3(u'', t) \exp(i(u''u + \omega t)) du'' dt = G(u, \Delta\omega + \omega_d) \cdot H(u) \quad (19)$$

For obtaining  $G(u, v)$  on the  $uv$  plane, the above-mentioned expression (19) is divided by  $H(u)$  as in the following expression (20). Subsequent arithmetic processing equivalent to that in the first arrangement example can yield the complex amplitude image  $g(\xi, \eta)$  of the object **2**.

[Math. 20]

$$G(u, \Delta\omega + \omega_d) = \frac{1}{H(u)} \iint s_3(u'', t) \exp(i(u''u + \omega t)) du'' dt \quad (20)$$

In the third arrangement example in which the light-receiving surface of the photodetector **46** is arranged on a given  $u''v''$  plane perpendicular to the optical axis in front or rear of the lens **40** in the structure of the observation device **1** in accordance with this embodiment, the arithmetic unit **50** performs the foregoing arithmetic processing, so as to obtain the image of the object **2**. That is, the arithmetic unit **50** acquires data of

the signal  $s_3(u'', t)$  employing the position  $u''$  on the  $u''v''$  plane and the time  $t$  as variables, performs a Fourier transform of the data of the signal  $s_3(u'', t)$  with respect to the variable  $u''$  and time variable  $t$  (the above-mentioned expression (19)), divides the data obtained by the Fourier transform by  $H$ , so as to yield  $G$  on the  $uv$  plane (the above-mentioned expression (20)), cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus obtained data  $G$  (the above-mentioned expression (14)), and performs a two-dimensional Fourier transform of thus cut-out data (the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object **2**. For obtaining the complex amplitude image  $g(\xi, \eta)$  in focus, the initial phase resulting from optical conditions of scattered light and reference light must be corrected as appropriate.

FIG. 29 is a diagram illustrating structures of the photodetector **46** and arithmetic unit **50** in the third arrangement example performing the foregoing arithmetic processing. The arithmetic unit **50** comprises a first Fourier transform device **51**, a second Fourier transform unit **52**, a specific region cutting device **55**, and a quadratic phase dividing device **57**. The second Fourier transform unit **52** includes a third Fourier transform device **53** and a fourth Fourier transform device **54**. The first Fourier transform device **51** performs a Fourier transform of the data of the signal  $s_3(u'', t)$  employing the position  $u''$  on the  $u''v''$  plane and the time  $t$  as variables with respect to the time variable  $t$  (Fourier transform with respect to the time variable  $t$  in the above-mentioned expression (19)). The fourth Fourier transform device **54** arranged behind the first Fourier transform device **51** performs a Fourier transform with respect to the variable  $u''$  of the data obtained by the preceding Fourier transform (Fourier transform with respect to the variable  $u''$  in the above-mentioned expression (19)). The quadratic phase dividing device **57** divides the data obtained by the fourth Fourier transform device **54** by  $H$ , so as to yield  $G$  on the  $uv$  plane (the above-mentioned expression (20)). The specific region cutting device **55** cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus obtained data  $G$  (the above-mentioned expression (14)). The third Fourier transform device **53** performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega_d$  in the above-mentioned expression (15)). The fourth Fourier transform device **54** arranged behind the third Fourier transform device **53** performs a Fourier transform with respect to the variable  $u$  (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the first Fourier transform device **51**, fourth Fourier transform device **54**, third Fourier transform device **53**, and fourth Fourier transform device **54** are arranged in this order in the arithmetic unit **50** in the third arrangement example. The fourth Fourier transform device **54** arranged behind the first Fourier transform device **51** is not restricted to this position but may be arranged between the third Fourier transform device **53** and the fourth Fourier transform device **54** arranged behind the third Fourier transform device **53**, or in front of the first Fourier transform device **51**, for example. The fourth Fourier transform device **54** arranged behind the third Fourier transform device **53** is not restricted to this position but may be arranged between the fourth Fourier transform device **54** arranged behind the first Fourier transform device **51** and the third Fourier transform device **53**, or in front of the first Fourier transform device **51**,

for example. Using such arithmetic unit **50**, the signal  $s_3(u'', t)$  is subjected to arithmetic operations, whereby the image  $g(\xi, \eta)$  of the object **2** is obtained.

A special case of the third arrangement example corresponds to the first or second arrangement example. That is, the second arrangement example corresponds to a case where  $H(u, v)=1$  in the expression (17) in the third arrangement example. The first arrangement example corresponds to a case where the Fourier plane (Fraunhofer diffraction) is on the  $u''v''$  plane in the third arrangement example. The latter will be explained in the following.

Substituting the expression (18) into the expression (17) and expanding it yields the following expression (21). Letting  $z$  be infinity in the expression (21), the value of the exponential function within the integral in the right side is approximated by 1, whereby the expression (21) is approximated by the following expression (22). The expression (22) is equivalent to the expression (10). Therefore, a special case of the third arrangement example, i.e., a case where  $d=f$  in the expression (10), is the first arrangement example.

[Math. 21]

$$g''(u'', v'') = \frac{e^{ikz}}{i\lambda z} e^{i\frac{k}{2z}(u''^2 + v''^2)} \iint \left\{ g(\xi, \eta) e^{i\frac{k}{2z}(\xi^2 + \eta^2)} \right\} e^{-i\frac{2\pi}{\lambda z}(u''\xi + v''\eta)} d\xi d\eta \quad (21)$$

[Math. 22]

$$g''(u'', v'') = \frac{e^{ikz}}{i\lambda z} e^{i\frac{k}{2z}(u''^2 + v''^2)} \iint g(\xi, \eta) e^{-i\frac{2\pi}{\lambda z}(u''\xi + v''\eta)} d\xi d\eta \quad (22)$$

#### Fourth Arrangement Example

In the foregoing first, second, and third arrangement examples, details of arithmetic operations have been explained while omitting the initial phase  $\phi_0$  resulting from optical conditions of scattered light and reference light. A structure in which, as in the first arrangement example, the arithmetic unit **50** corrects the initial phase  $\phi_0$  included in a one-dimensional Fourier transform with respect to a time variable in the observation device **1** in which the light-receiving surface of the photodetector **46** is arranged on the back focal plane in the first direction of the lens **40**, which is also the back focal plane in the second direction of the lens **40**, will now be explained in detail as a fourth arrangement example. The lens **40** in the fourth arrangement example has a lens structure similar to that of the lens **40** in the first arrangement example illustrated in FIG. 12.

FIG. 30 is a diagram schematically illustrating an operation for obtaining a signal  $s_4(u_n, t)$  representing the sum of signals  $h_1$  to  $h_N$  on a line parallel to the  $v$  direction for each  $u_n$  when the fourth arrangement example is employed in the observation device **1** of this embodiment. In FIG. 30, sign  $\Sigma$  represents an arithmetic operation for summing of signals  $h_1$  to  $h_N$ . The signal  $s_4(u, t)$  indicating the sum of signals  $h(v)$  on a line parallel to the  $v$  direction with respect to a given  $u$ -coordinate value is calculated as with  $s_1$  represented by the expression (11).

When taking account of the initial phase  $\phi_0$ , which is omitted for yielding the expression (13) in the first arrangement example, a one-dimensional Fourier transform of the signal  $s_4(u, t)$  employing the position  $u$  on the  $uv$  plane and the time  $t$  as variables with respect to the time variable  $t$  is performed by an arithmetic operation represented by the following expression (23) similar to that for  $s_1(u, t)$ .

[Math. 23]

$$\int s_4(u, t) \exp(-i\omega t) dt = aG(u, \Delta v + v) \exp(i\phi_0) \quad (23)$$

When the left side of the expression (23) is represented as  $S_4(u, \Delta v + v)$ , multiplying both sides of the expression (23) by the term  $\exp(-i\phi_0)$  including the initial phase  $\phi_0$  leaves the constant of proportionality  $a$  and function  $G$  alone in the right side of the expression (23) as with the right side of the expression (13). That is, the correction of the initial phase  $\phi_0$  is equivalent to multiplying the signal  $S_4(u, \Delta v + v)$  by  $\exp(-i\phi_0)$ .

Thus, multiplying the signal  $S_4(u, \Delta v + v)$  by  $\exp(-i\phi_0)$  can yield a two-dimensional Fourier transform image  $G(u, \Delta v + v)$  for the complex amplitude image  $g(\xi, \eta)$  of the object 2. This Fourier transform image  $G(u, \Delta v + v)$  is equivalent to that in the first arrangement example, whereby subsequent arithmetic processing similar to that in the first arrangement example can yield the complex amplitude image  $g(\xi, \eta)$  of the object 2.

In the fourth arrangement example in which the light-receiving surface of the photodetector 46 is arranged on the back focal plane (uv plane) of the lens 40 in the structure of the observation device 1 in accordance with this embodiment, the arithmetic unit 50 performs the foregoing arithmetic processing, so as to obtain the image of the object 2. That is, the arithmetic unit 50 acquires data of the signal  $s_4(u, t)$  employing the position  $u$  on the uv plane and the time  $t$  as variables, performs a one-dimensional Fourier transform of the data of the signal  $s_4(u, t)$  with respect to the time variable  $t$  (the above-mentioned expression (23)), corrects the data obtained by the one-dimensional Fourier transform with the initial phase  $\phi_0$ , cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data  $G$  (the above-mentioned expression (14)), and performs a two-dimensional Fourier transform of thus cut-out data (the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object 2.

FIG. 31 is a diagram illustrating the structure of the arithmetic unit 50 in the fourth arrangement example performing the foregoing arithmetic processing. The arithmetic unit 50 comprises a first Fourier transform device 51 for performing a one-dimensional Fourier transform of data of the signal  $s_4(u, t)$  employing the position  $u$  on the uv plane and the time  $t$  as variables with respect to the time variable  $t$  (the above-mentioned expression (23)), an initial phase correction device 56 for correcting the data obtained by the one-dimensional Fourier transform with the initial phase  $\phi_0$ , a specific region cutting device 55 for cutting out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data  $G$  (the above-mentioned expression (14)), a third Fourier transform device 53 for performing a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega_d$  in the above-mentioned expression (15)), and a fourth Fourier transform device 54 for performing a Fourier transform with respect to the variable  $u$  (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the first Fourier transform device 51, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order in the arithmetic unit 50 in the fourth arrangement example. The fourth Fourier transform device 54 is not restricted to this position but may be arranged between the first Fourier transform device 51 and the third Fourier transform device 53, or in front of the first Fourier transform device 51, for example. Using such arithmetic unit

50, the signal  $s_1(u, t)$  is subjected to arithmetic operations, whereby the image  $g(\xi, \eta)$  of the object 2 is obtained.

As illustrated in the fourth arrangement example, correcting the initial phase  $\phi_0$  resulting from optical conditions of reference light and scattered light can prevent the complex amplitude image  $g(\xi, \eta)$  of the object 2 from being blurred by the initial phase  $\phi_0$ , whereby the complex amplitude image  $g(\xi, \eta)$  in focus can be obtained. Though processing for correcting the initial phase  $\phi_0$  has been explained in the arrangement examples in which the light-receiving surface of the photodetector 46 is arranged so as to coincide with the back focal plane of the lens 40 by way of example, the initial phase  $\phi_0$  can be corrected by similar arithmetic operations in other arrangement examples as well. While all the following arrangement examples illustrate those in which the initial phase  $\phi_0$  is corrected, the processing for correcting the initial phase  $\phi_0$  is not always necessary.

#### Fifth Arrangement Example

In the second arrangement example explained above, the first Fourier transform device 51, fourth Fourier transform device 54, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order in the arithmetic unit 50. A structure in which, as in the second arrangement example, the arithmetic unit 50 is simplified in the observation device 1 in which the light-receiving surface of the photodetector 46 is arranged on a plane where an image of an object is formed in the first direction by the lens 40, which is also a plane (u'v' plane) on which the image of the object is formed in the second direction, will now be explained as the fifth arrangement example as compared with the second arrangement example. The lens 40 in the fifth example has a lens structure similar to that in the second arrangement example illustrated in FIG. 23.

The uv plane in FIG. 23 illustrates the back focal plane of the lens 403. In the second arrangement example, the light-receiving surface of the photodetector 46 is arranged on the back focal plane of the lens 404 having the front focal plane on the uv plane. In FIG. 23, X is the first direction and coincides with u'. Y is the second direction and coincides with v'. Z is a direction orthogonal to the first and second directions. The lenses 403, 404, each of which is a spherical lens, exhibit the same action in the X and Y directions. Since the X and Y directions are orthogonal to each other, Fourier transforms in the X and Y directions have no influences on each other and pose no problems mathematically even when considered independently from each other.

In FIG. 23, the action of the lens 404 in the second arrangement example is equivalent to optically performing respective one-dimensional Fourier transforms of an image appearing on the uv plane with respect to the variables  $u$  and  $v$ . The arithmetic unit 50 in the second arrangement example performs a first two-dimensional Fourier transform of the signal  $s_2(u', t)$  by the expression (16), thereby yielding  $G(u, \Delta\omega + \omega_d)$ . The first two-dimensional Fourier transform is equivalent to performing respective one-dimensional Fourier transforms with respect to the time variable  $t$  and the variable  $u'$ .

The arithmetic unit 50 in the second arrangement example performs a second two-dimensional inverse Fourier transform of a distribution  $G(u, \omega_d)$  cutting out a frequency region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta\omega$  acting as the center frequency from the data  $G(u, \Delta\omega + \omega_d)$ , so as to yield  $g(u', t)$ . The second two-dimensional Fourier transform is equivalent to performing respective one-dimensional Fourier transforms with respect to the temporal frequency  $\omega_d$  and the variable  $u$ . That is, the arithmetic unit 50 in the second arrangement example performs the one-dimensional Fourier



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transform with respect to the variable  $u'$  in the first two-dimensional Fourier transform and the one-dimensional Fourier transform with respect to the variable  $u$  in the second two-dimensional Fourier transform, thereby doing no Fourier transform in the  $u'$  direction. Therefore, it can be said that

redundancy in Fourier transforms exists in the  $u$  direction or  $u'$  direction (first direction) in the arithmetic unit **50** for receiving the output of the photodetector **46** in the second arrangement example.

FIG. **32** illustrates a schematic diagram of arithmetic operations performed by the arithmetic unit **50** in the fifth arrangement example reducing the number of Fourier transforms by simplifying the second arrangement example. In the fifth arrangement example in which the light-receiving surface of the photodetector **46** is arranged on a plane where an image of the object **2** is formed in the first direction by the lens **404**, which is also a plane ( $u'v'$  plane) where an image of the object **2** is formed in the second direction in the observation device **1**, the arithmetic unit **50** performs the following arithmetic processing, so as to obtain the image of the object **2**. That is, the lens **404** constituting the lens **40** optically performs a Fourier transform in the first direction. The arithmetic unit **50** acquires data of the signal  $s_5(u', t)$  employing the position  $u'$  on the  $uv$  plane and the time  $t$  as variables and performs a one-dimensional Fourier transform of the data of the signal  $s_5(u', t)$  with respect to the time variable  $t$  (the above-mentioned expression (23)). It corrects the data obtained by the one-dimensional Fourier transform with the initial phase  $\phi_0$  and cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data  $G$  (the above-mentioned expression (14)). It performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega_d$  in the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object **2**.

FIG. **33** is a diagram illustrating the structure of the arithmetic unit **50** in the fifth arrangement example performing the foregoing arithmetic processing. The arithmetic unit **50** comprises the lens **40**, a first Fourier transform device **51**, a third Fourier transform device **53**, an initial phase correction device **56**, and a specific region cutting device **55**. The lens **404** optically performs a Fourier transform of a Fraunhofer diffraction image of the object **2** produced on the back focal plane of the lens **403**. The first Fourier transform device **51** performs a one-dimensional Fourier transform with respect to the time variable  $t$  of data  $s_5(u', \omega)$  obtained by the preceding Fourier transform (Fourier transform with respect to the time variable  $t$  in the above-mentioned expression (16)). The initial phase correction device **56** corrects the data obtained by the one-dimensional Fourier transform with the initial phase  $\phi_0$ . The specific region cutting device **55** cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data  $G$  (the above-mentioned expression (14)). The third Fourier transform device **53** performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the lens **404**, first Fourier transform device **51**, and third Fourier transform device **53** are arranged in this order in the arithmetic unit **50** in the fifth arrangement example. Using such arithmetic unit **50**, the signal  $s_5(u', t)$  is subjected to arithmetic operations, whereby the image  $g(\xi, \eta)$  of the object **2** is obtained. A Fraunhofer diffraction image appears on the back focal plane of the lens **403**. The lens **404** further per-

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forms a Fourier transform, so as to form an image on the light-receiving surface of the photodetector **46**. That is, the lens **404** optically performs Fourier transforms in the first and second directions and thus includes the action of the Fourier transform in the first direction. When compared with the arithmetic unit in the first arrangement example, the fifth arrangement example is equivalent to a state where the lens **404** optically acts as the fourth Fourier transform device **54** in the arithmetic unit of the first arrangement example.

#### Sixth Arrangement Example

In the observation device **1** in which the light-receiving surface of the photodetector **46** is arranged on a  $u''v''$  plane (plane where a Fresnel diffraction image of the object is formed) which is a given plane perpendicular to the optical axis in front or rear of the lens **40** in both of the first and second directions of the lens **40** as in the third arrangement example, a structure in which the order of arranging arithmetic devices in the arithmetic unit **50** of the third arrangement example is changed will now be explained as the sixth arrangement example. The lens **40** in the sixth example has a lens structure similar to that in the third arrangement example illustrated in FIG. **28**.

The arithmetic unit **50** in the third arrangement example performs a first two-dimensional Fourier transform of the signal  $s_3(u'', t)$  issued from the photodetector **46**, so as to yield  $G(u, \Delta\omega + \omega_d)H(u)$  as in the expression (19). The first two-dimensional Fourier transform is equivalent to performing respective one-dimensional Fourier transforms with respect to the time variable  $t$  and the variable  $u''$ . The arithmetic unit **50** in the third arrangement example divides a distribution  $G(u, \omega_d)H(u)$ , cutting out a frequency region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta\omega$  acting as the center frequency from the data  $G(u, \Delta\omega + \omega_d)H(u)$ , by a quadratic phase  $H(u)$  and then performs a second two-dimensional inverse Fourier transform, so as to yield  $g(\xi, \eta)$ . The action of the second two-dimensional Fourier transform is equivalent to performing respective one-dimensional Fourier transforms with respect to the temporal frequency  $\omega_d$  and the variable  $u$ .

When attention is directed to arithmetic operations in the first direction ( $u''$  and  $u'$  directions), it is constructed by the one-dimensional Fourier transform with respect to the variable  $u''$ , the division by the quadratic phase  $H(u)$  (quadratic phase dividing device **57**), and the one-dimensional Fourier transform with respect to the variable  $u$  in this order. In the following, these arithmetic operations concerning the first direction will collectively be referred to as quadratic phase correction unit **60**.

The arithmetic unit **50** in the third arrangement example is equivalent to a structure in which the quadratic phase dividing device **57** is added to the arithmetic unit **50** in the second arrangement example. The arithmetic unit **50** in the third arrangement example is also equivalent to a structure in which the quadratic phase correction unit **60** is added to the arrangement example **50** in the fifth arrangement example.

As the lens **40** in the sixth example, one having a structure including the objective lens **405** and a lens **406** such as those illustrated in FIG. **28** is used, while the photodetector **46** is arranged on a given plane perpendicular to the optical axis in front or rear thereof, as in the third example.

FIG. **34** illustrates a schematic diagram of arithmetic operations performed by the arithmetic unit **50** in the sixth arrangement example. The sixth arrangement example includes the lens **40** similar to that in the third arrangement example, while the quadratic phase correction unit **60** is arranged behind the arithmetic unit **50** in the fifth arrangement example. In the sixth arrangement example, the arith-

metic unit **50** performs the following arithmetic processing, so as to obtain the image of the object **2**. That is, the arithmetic unit **50** acquires data of a signal  $s_g(u'', t)$  employing the position  $u''$  on the  $u''v''$  plane and the time  $t$  as variables, performs a Fourier transform of the data of the signal  $s_g(u'', t)$  with respect to the time variable  $t$  (Fourier transform with respect to the time variable  $t$  in the above-mentioned expression (19)), corrects the data obtained by this one-dimensional Fourier transform with the initial phase  $\phi_0$ , cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data  $G$  (the above-mentioned expression (14)), performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega$  in the above-mentioned expression (15)), does a one-dimensional Fourier transform of the data obtained by the Fourier transform with respect to the variable  $u''$  (Fourier transform with respect to the variable  $u''$  in the above-mentioned expression (19)), divides the result by  $H$ , so as to obtain  $G$  with respect to only  $u$ -direction of the  $uv$  plane (the above-mentioned expression (20)), and performs a one-dimensional Fourier transform of thus obtained data (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)), thereby yielding the image  $g(\xi, \eta)$  of the object **2**.

As in the foregoing, the sixth arrangement example decomposes the two two-dimensional Fourier transforms in the third arrangement example into one-dimensional Fourier transforms in the first direction and other directions and rearranges these one-dimensional Fourier transforms, and its mathematical operation method is the same as that in the third arrangement example. The quadratic phase correction unit **60** exhibits the action in the first direction of the lens **404** in the second arrangement example together with the action in the first direction of the lens **406** constituting the lens **40** in the third arrangement example. Therefore, removing the lens **406** and the quadratic phase correction unit **60** from the sixth arrangement example and arranging the light-receiving surface of the photodetector **46** on the  $uv$  plane makes the first arrangement example.

FIG. **35** is a diagram illustrating the structure of the arithmetic unit **50** in the sixth arrangement example performing the foregoing arithmetic processing. The arithmetic unit **50** comprises a first Fourier transform device **51**, a second Fourier transform unit **52**, a specific region cutting device **55**, an initial phase correction device **56**, and a quadratic phase dividing device **57**. The second Fourier transform unit **52** includes a third Fourier transform device **53** and two fourth Fourier transform devices **54**. The first Fourier transform device **51** performs a one-dimensional Fourier transform of data of the signal  $s_g(u'', t)$  employing the time  $t$  on the  $u''v''$  plane as a variable with respect to the time variable  $t$  (Fourier transform with respect to the time variable  $t$  in the above-mentioned expression (19)). The initial phase correction device **56** corrects the data obtained by the one-dimensional Fourier transform with the initial phase  $\phi_0$ . The specific region cutting device **55** cuts out data in a region including the range of a Nyquist frequency  $f_{nyq}$  in upper and lower region of the difference frequency  $\Delta f$  from thus corrected data (the above-mentioned expression (14)). The third Fourier transform device **53** performs a one-dimensional Fourier transform of thus cut-out data with respect to the temporal frequency  $\omega_d$  (Fourier transform with respect to the temporal frequency  $\omega$  in the above-mentioned expression (15)). The fourth Fourier transform device **54** arranged behind the third Fourier transform device **53** performs a one-dimensional Fourier transform with respect to the variable  $u''$  (Fourier

transform with respect to the variable  $u''$  in the above-mentioned expression (19)). The quadratic phase dividing device **57** divides thus Fourier-transformed data by the quadratic phase  $H(u)$  (the above-mentioned expression (20)). The fourth Fourier transform device **54** arranged behind the quadratic phase dividing device **57** performs a one-dimensional Fourier transform with respect to the variable  $u$  (Fourier transform with respect to the variable  $u$  in the above-mentioned expression (15)). When attention is directed to the Fourier transform units, the first Fourier transform device **51**, third Fourier transform device **53**, and fourth Fourier transform devices **54**, **54** are arranged in this order in the arithmetic unit **50** in the sixth arrangement example. The fourth Fourier transform device **54** arranged behind the third Fourier transform device **53** is not restricted to this position but may be arranged between the first Fourier transform device **51** and the third Fourier transform device **53**, or in front of the first Fourier transform device **51**, for example. The fourth Fourier transform device **54** arranged behind the other fourth Fourier transform device **54** is not restricted to this position but may be arranged between the first Fourier transform device **51** and the third Fourier transform device **53**, or in front of the first Fourier transform device **51**, for example. By using such arithmetic devices, the arithmetic unit **50** performs arithmetic operations for the signal  $s_g(u'', t)$ , thereby yielding the image  $g(\xi, \eta)$  of the object **2**.

The lens **40** arranged between the object **2** and the photodetector **46** in the observation device **1** of this embodiment exhibits the same action in the  $x$  and  $y$  directions for scattered light in the foregoing explanation. However, the optical system between the object **2** and the photodetector **46** may magnify or reduce the Fourier image by a relay optical system having an anamorphic magnification.

#### Seventh Arrangement Example

The seventh arrangement example will now be explained. The seventh arrangement example is the same as the first arrangement example except for the structure of the lens **40**. In the seventh arrangement example, the light-receiving surface of the photodetector **46** is arranged on a plane where a Fraunhofer diffraction image of the object **2** is formed in the  $x$  direction (first direction) by the lens **40**, which is also a plane where a Fraunhofer diffraction image of the object **2** is formed in the  $y$  direction (second direction). The lens **40** in the seventh arrangement example is arranged between the object **2** and the photodetector **46**.

FIG. **36** illustrates details of the lens **40** in the seventh arrangement example. In the seventh arrangement example, the lens **40** is constructed by three lenses composed of the lenses **403**, **404** constituting the lens **40** in the second arrangement example and an additional lens **LS2**. Each of the three lenses constructing the lens **40** is a spherical lens. In the image-forming action by the lens, the spherical lenses exhibit the same actions in the  $x$  and  $y$  directions. The beam splitter **12** is arranged on the back focal plane of the lens **403** constituting the lens **40** so as to split the substantially zero-order light in two. The light reflected by the beam splitter **12** is fed to the lens **60** as the second light.

The lens **40** in the second arrangement example forms an object image on a plane **IP**. In each of the  $x$  and  $y$  directions, an image of the object **2** is once formed on the plane **IP** by the lenses **403**, **404**. The front focal plane of the lens **LS2** coincides with the plane **IP**. The back focal plane of the lens **LS2** coincides with the light-receiving surface of the photodetector **46**. Thus, a Fraunhofer diffraction image of the object **2** is formed on the light-receiving surface of the photodetector **46** in each of the  $x$  and  $y$  directions of the lens.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the uv plane as in the first arrangement example. In the first arrangement example, Fraunhofer diffraction images appear on the uv plane in the u and v directions. In the seventh arrangement example, Fraunhofer diffraction images appear in the u and v directions. The seventh arrangement example differs from the first arrangement example in the structure of the lens 40.

Let  $s_7(u, t)$  be a signal representing the sum of signals on a line parallel to the v direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_7(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_1(u, t)$  obtained by the first arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_7(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Eighth Arrangement Example

The eighth arrangement example will now be explained. The eighth arrangement example is the same as the first arrangement example except for the structure of the lens 40. In the eighth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where a Fraunhofer diffraction image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where an image of the object 2 is formed in the y direction (second direction). The lens 40 in the eighth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 37 illustrates details of the lens 40 in the eighth arrangement example. In the eighth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens 40, the lenses 403, 404 are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, the cylindrical lenses exhibit different actions in the x and y directions. Let  $f_{LS1}$ ,  $f_{LS2}$ , and  $f_{LS3}$  be the focal lengths of the lenses LS1, LS2, LS3, respectively. Suppose that these focal lengths have the relationships of  $f_{LS1}=f_{LS3}$ , and  $f_{LS2}=2f_{LS1}=2f_{LS3}$ . The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the upper side of FIG. 37. In the y direction, on the other hand, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the lower side of FIG. 37.

In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. Subsequently, a Fraunhofer diffraction image of the image is formed on the light-receiving surface under an action of the lens LS2 which is the same as that in the seventh arrangement example. In the y

direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. The lenses LS1, LS3 constitute a so-called 4f optical system. The 4f optical system is an optical system in which the back focal plane of the lens LS1 coincides with the front focal plane of the lens LS3, so that an image of the front focal plane of the lens LS1 is formed on the back focal plane of the lens LS3. Thus, the Fraunhofer diffraction image and image of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40 in the eighth arrangement example.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the uv plane as in the first arrangement example. In the first arrangement example, Fraunhofer diffraction images appear on the uv plane in the u and v directions. In the eighth arrangement example, a Fraunhofer diffraction image and an object image appear in the u and v directions, respectively. Let  $s_8(u, t)$  be a signal representing the sum of signals on a line parallel to the v direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_8(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_1(u, t)$  obtained by the first arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_8(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Ninth Arrangement Example

The ninth arrangement example will now be explained. The ninth arrangement example is the same as the first arrangement example except for the structure of the lens 40. In the ninth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where a Fraunhofer diffraction image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where a Fresnel diffraction image of the object is formed in the y direction (second direction). The lens 40 in the ninth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 38 illustrates details of the lens 40 in the ninth arrangement example. In the ninth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens 40, the lenses 403, 404 are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, the cylindrical lenses exhibit different actions in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the upper side of FIG. 38. In the y direction, on the other hand, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the lower side of FIG. 38.

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In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. Subsequently, a Fraunhofer diffraction image of the image is formed on the light-receiving surface of the photodetector 46 under an action of the lens LS2 which is the same as that in the seventh arrangement example. In the y direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. The lenses LS1, LS3 do not construct a so-called 4f optical system. That is, as illustrated in the lower side of FIG. 38, the front focal plane of the lens LS3 does not coincide with the back focal plane of the lens LS1. Therefore, none of images of the object 2 and Fourier images thereof is formed on the light-receiving surface of the photodetector 46. Thus, the Fraunhofer and Fresnel diffraction images of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the uv plane as in the first arrangement example. In the first arrangement example, Fraunhofer diffraction images appear on the uv plane in the u and v directions. In the ninth arrangement example, the Fraunhofer and Fresnel diffraction images of the object appear in the u and v directions, respectively. Let  $s_9(u, t)$  be a signal representing the sum of signals on a line parallel to the v direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_9(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_1(u, t)$  obtained by the first arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_9(u, t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Tenth Arrangement Example

The tenth arrangement example will now be explained. The tenth arrangement example is the same as the second or fifth arrangement example except for the structure of the lens 40. In the tenth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where an image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where a Fraunhofer diffraction image of the object 2 is formed in the y direction (second direction). The lens 40 in the tenth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 39 illustrates details of the lens 40 in the tenth arrangement example. In the tenth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens 40, the lenses 403, 404 are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, the cylindrical lenses exhibit different actions in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the upper side of FIG. 39. In the y direction, on the other hand, the lenses LS1, LS3 have no curvature and thus do not

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contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the lower side of FIG. 39.

In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. The lenses LS1, LS3 constitute a so-called 4f optical system. The 4f optical system is an optical system in which the back focal plane of the lens LS1 coincides with the front focal plane of the lens LS3, so that an image of the front focal plane of the lens LS1 is formed on the back focal plane of the lens LS3. In the y direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. Subsequently, a Fraunhofer diffraction image of the image is formed on the light-receiving surface of the photodetector 46 under an action of the lens LS2 which is the same as that in the seventh arrangement example. Thus, the image and Fraunhofer diffraction image of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the u'v' plane as in the second arrangement example. In the second or fifth arrangement example, images of the object 2 appear on the u'v' plane in the u' and v' directions. In the tenth arrangement example, an image of the object 2 and a Fraunhofer diffraction image of the object appear in the u' and v' directions, respectively. Let  $s_{10}(u', t)$  be a signal representing the sum of signals on a line parallel to the v' direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{10}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_2(u', t)$  or  $s_5(u', t)$  obtained by the second or fifth arrangement example and the arithmetic device structure for performing this processing. That is, the light source 10, lens 40, photodetector 46, first Fourier transform device 51, fourth Fourier transform device 54, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order when employing the structure of the second arrangement example. The light source 10, lens 40, photodetector 46, first Fourier transform device 51, and third Fourier transform device 53 are arranged in this order when employing the structure of the fifth arrangement example. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{10}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Eleventh Arrangement Example

The eleventh arrangement example will now be explained. The eleventh arrangement example is the same as the second or fifth arrangement example except for the structure of the lens 40. In the eleventh arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where an image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where an image of the object 2 is formed in the y direction (second direction). The lens 40 in the eleventh arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 40 illustrates details of the lens 40 in the eleventh arrangement example. In the eleventh arrangement example, the lens 40 is constructed by four lenses composed of the lenses 403, 404 constituting the lens 40 used in the second arrangement example and additional lenses LS1, LS3. The four lenses constituting the lens 40 are spherical lenses. In the

image-forming action by the lens, these spherical lenses exhibit the same action in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

Therefore, in each of the x and y directions, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. The lenses LS1, LS3 constitute a so-called 4f optical system. The 4f optical system is an optical system in which the back focal plane of the lens LS1 coincides with the front focal plane of the lens LS3, so that an image of the front focal plane of the lens LS1 is formed on the back focal plane of the lens LS3. Thus, the lens 40 forms an image of the object 2 on the light-receiving surface of the photodetector 46 in each of the x and y directions.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the  $u'v'$  plane as in the second arrangement example. In the second or fifth arrangement example, images of the object 2 appear on the  $u'v'$  plane in the  $u'$  and  $v'$  directions. Similarly, images of the object 2 appear on the  $u'v'$  plane in the  $u'$  and  $v'$  directions in the eleventh arrangement example. The eleventh arrangement example differs from the second arrangement example in the structure of the lens 40. Let  $s_{11}(u', t)$  be a signal representing the sum of signals on a line parallel to the  $v'$  direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{11}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_2(u', t)$  or  $s_5(u', t)$  obtained by the second or fifth arrangement example and the arithmetic device structure for performing this processing. That is, the light source 10, lens 40, photodetector 46, first Fourier transform device 51, fourth Fourier transform device 54, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order when employing the structure of the second arrangement example. The light source 10, lens 40, photodetector 46, first Fourier transform device 51, and third Fourier transform device 53 are arranged in this order when employing the structure of the fifth arrangement example. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{11}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Twelfth Arrangement Example

The twelfth arrangement example will now be explained. The twelfth arrangement example is the same as the second or fifth arrangement example except for the structure of the lens 40. In the twelfth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where an image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where a Fresnel diffraction image of the object 2 is formed in the y direction (second direction). The lens 40 in the twelfth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 41 illustrates details of the lens 40 in the twelfth arrangement example. In the twelfth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 used in the second arrangement example and additional lenses LS1, LS2, LS3.

cylindrical lenses. In the image-forming action by the lens, these cylindrical lenses exhibit different actions in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the upper side of FIG. 41. In the y direction, on the other hand, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the lower side of FIG. 41.

In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. The lenses LS1, LS3 constitute a so-called 4f optical system. The 4f optical system is an optical system in which the back focal plane of the lens LS1 coincides with the front focal plane of the lens LS3, so that an image of the front focal plane of the lens LS1 is formed on the back focal plane of the lens LS3. In the y direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. The front focal plane of the lens LS2 differs from the plane IP of the image of the object 2, while the back focal plane of the lens LS2 differs from the light-receiving surface of the photodetector 46. Therefore, a Fresnel diffraction image of the image is formed on the light-receiving surface. Thus, the image and Fresnel diffraction image of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40 in the twelfth arrangement example.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the  $u'v'$  plane as in the second or fifth arrangement example. In the second or fifth arrangement example, images of the object 2 appear on the  $u'v'$  plane in the  $u'$  and  $v'$  directions. In the twelfth arrangement example, an image of the object 2 and a Fresnel diffraction image of the object appear in the  $u'$  and  $v'$  directions, respectively. Let  $s_{12}(u', t)$  be a signal representing the sum of signals on a line parallel to the  $v'$  direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{12}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_2(u', t)$  or  $s_5(u', t)$  obtained by the second or fifth arrangement example and the arithmetic device structure for performing this processing. That is, the light source 10, lens 40, photodetector 46, first Fourier transform device 51, fourth Fourier transform device 54, third Fourier transform device 53, and fourth Fourier transform device 54 are arranged in this order when employing the structure of the second arrangement example. The light source 10, lens 40, photodetector 46, first Fourier transform device 51, and third Fourier transform device 53 are arranged in this order when employing the structure of the fifth arrangement example. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{12}(u', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Thirteenth Arrangement Example

The thirteenth arrangement example will now be explained. The thirteenth arrangement example is the same as

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the third or sixth arrangement example except for the structure of the lens 40. In the thirteenth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where a Fresnel diffraction image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where a Fraunhofer diffraction image of the object 2 is formed in the y direction (second direction). The lens 40 in the thirteenth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 42 illustrates details of the lens 40 in the thirteenth arrangement example. In the thirteenth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 used in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens 40, the lenses 403, 404 are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, these cylindrical lenses exhibit different actions in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the upper side of FIG. 42. In the y direction, on the other hand, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the lower side of FIG. 42.

In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. The lenses LS1, LS3 do not construct a so-called 4f optical system. That is, as illustrated in the upper side of FIG. 42, the front focal plane of the lens LS3 does not coincide with the back focal plane of the lens LS1. Therefore, none of images of the object 2 and Fraunhofer diffraction images thereof is formed on the light-receiving surface. In the y direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. Subsequently, a Fraunhofer diffraction image of the image is formed on the light-receiving surface under an action of the lens LS2 which is the same as that in the seventh arrangement example. Thus, the Fresnel and Fraunhofer diffraction images of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the  $u''v''$  plane as in the third or sixth arrangement example. In the third or sixth arrangement example, Fresnel diffraction images of the object 2 appear on the  $u''v''$  plane in the  $u''$  and  $v''$  directions. In the thirteenth arrangement example, the Fresnel and Fraunhofer diffraction images of the object appear in the  $u''$  and  $v''$  directions, respectively. Let  $s_{13}(u'', t)$  be a signal representing the sum of signals on a line parallel to the  $v''$  direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{13}(u'', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_3(u'', t)$  or  $s_6(u'', t)$  obtained by the third or sixth arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining

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the complex amplitude image  $g(\xi, \eta)$  according to  $s_{13}(u'', t)$  issued from the photodetector 46 and the arithmetic device structure for performing this processing will not be explained.

#### Fourteenth Arrangement Example

The fourteenth arrangement example will now be explained. The fourteenth arrangement example is the same as the third or sixth arrangement example except for the structure of the lens 40. In the fourteenth arrangement example, the light-receiving surface of the photodetector 46 is arranged on a plane where a Fresnel diffraction image of the object 2 is formed in the x direction (first direction) by the lens 40, which is also a plane where an image of the object 2 is formed in the y direction (second direction). The lens 40 in the fourteenth arrangement example is arranged between the object 2 and the photodetector 46.

FIG. 43 illustrates details of the lens 40 in the fourteenth arrangement example. In the fourteenth arrangement example, the lens 40 is constructed by five lenses composed of the lenses 403, 404 constituting the lens 40 used in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens 40, the lenses 403, 404 are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, these cylindrical lenses exhibit different actions in the x and y directions. The beam splitter 12 is arranged on the back focal plane of the lens 403 constituting the lens 40 so as to split the substantially zero-order light in two. The light reflected by the beam splitter 12 is fed to the lens 60 as the second light.

In the x direction, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses 403, 404, LS2 are arranged as illustrated in the upper side of FIG. 43. In the y direction, on the other hand, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses 403, 404, LS1, LS3 are arranged as illustrated in the lower side of FIG. 43.

In the x direction, an image of the object 2 is once formed on a plane IP by the lenses 403, 404. The front focal plane of the lens LS2 differs from the plane IP of the image of the object 2, while the back focal plane of the lens LS2 differs from the light-receiving surface of the photodetector 46. Therefore, a Fresnel diffraction image of the image is formed on the light-receiving surface. In the y direction, on the other hand, an image of the object 2 is once formed on the plane IP by the lenses 403, 404. The lenses LS1, LS3 constitute a so-called 4f optical system. The 4f optical system is an optical system in which the back focal plane of the lens LS1 coincides with the front focal plane of the lens LS3, so that an image of the front focal plane of the lens LS1 is formed on the back focal plane of the lens LS3. Thus, the Fresnel diffraction image and image of the object 2 are formed on the light-receiving surface of the photodetector 46 in the x and y directions, respectively, by the lens 40.

A method of processing a signal obtained in the photodetector 46 by thus constructed lens 40 will now be explained. Let the coordinate system on the light-receiving surface of the photodetector 46 be the  $u''v''$  plane as in the third or sixth arrangement example. In the third or sixth arrangement example, Fresnel diffraction images of the object 2 appear on the  $u''v''$  plane in the  $u''$  and  $v''$  directions. In the fourteenth arrangement example, the Fresnel diffraction image and image of the object 2 appear in the  $u''$  and  $v''$  directions, respectively. Let  $s_{14}(u'', t)$  be a signal representing the sum of signals on a line parallel to the  $v''$  direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi,$

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$\eta$ ) according to  $s_{14}(u'', t)$  issued from the photodetector **46** and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_3(u'', t)$  or  $s_6(u'', t)$  obtained by the third or sixth arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{14}(u'', t)$  issued from the photodetector **46** and the arithmetic device structure for performing this processing will not be explained.

#### Fifteenth Arrangement Example

The fifteenth arrangement example will now be explained. The fifteenth arrangement example is the same as the third or sixth arrangement example except for the structure of the lens **40**. In the fifteenth arrangement example, the light-receiving surface of the photodetector **46** is arranged on a plane where a Fresnel diffraction image of the object **2** is formed in the x direction (first direction) by the lens **40**, which is also a plane where a Fresnel diffraction image of the object **2** is formed in the y direction (second direction). The lens **40** in the fifteenth arrangement example is arranged between the object **2** and the photodetector **46**.

FIG. **44** illustrates details of the lens **40** in the fifteenth arrangement example. In the fifteenth arrangement example, the lens **40** is constructed by five lenses composed of the lenses **403**, **404** constituting the lens **40** used in the second arrangement example and additional lenses LS1, LS2, LS3. In the five lenses constituting the lens **40**, the lenses **403**, **404** are spherical lenses, while the lenses LS1, LS2, LS3 are cylindrical lenses. In the image-forming action by the lens, these cylindrical lenses exhibit different actions in the x and y directions. The beam splitter **12** is arranged on the back focal plane of the lens **403** constituting the lens **40** so as to split the substantially zero-order light in two. The light reflected by the beam splitter **12** is fed to the lens **60** as the second light.

In the x direction, the lenses LS1, LS3 have no curvature and thus do not contribute to forming images. Therefore, the lens structure in the x direction is equivalent to a structure in which only the lenses **403**, **404**, LS2 are arranged as illustrated in the upper side of FIG. **44**. In the y direction, on the other hand, the lens LS2 has no curvature and thus does not contribute to forming images. Therefore, the lens structure in the y direction is equivalent to a structure in which only the lenses **403**, **404**, LS1, LS3 are arranged as illustrated in the lower side of FIG. **44**.

In the x direction, an image of the object **2** is once formed on a plane IP by the lenses **403**, **404**. The front focal plane of the lens LS2 differs from the plane IP of the image of the object **2**, while the back focal plane of the lens LS2 differs from the light-receiving surface of the photodetector **46**. Therefore, a Fresnel diffraction image of the image is formed on the light-receiving surface. In the y direction, on the other hand, an image of the object **2** is once formed on the plane IP by the lenses **403**, **404**. The lenses LS1, LS3 do not construct a so-called 4f optical system. That is, as illustrated in the lower side of FIG. **44**, the front focal plane of the lens LS3 does not coincide with the back focal plane of the lens LS1. Therefore, none of images of the object **2** and Fraunhofer diffraction images thereof is formed on the light-receiving surface. Thus, the Fresnel diffraction images of the object **2** are formed on the light-receiving surface of the photodetector **46** in both of the x and y directions by the lens **40**.

A method of processing a signal obtained in the photodetector **46** by thus constructed lens **40** will now be explained. Let the coordinate system on the light-receiving surface of the photodetector **46** be the  $u''v''$  plane as in the third or sixth

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arrangement example. In the third or sixth arrangement example, Fresnel diffraction images of the object **2** appear on the  $u''v''$  plane in the  $u''$  and  $v''$  directions. The Fresnel diffraction images of the object **2** also appear in the  $u''$  and  $v''$  directions in the fifteenth arrangement example. The fifteenth arrangement example differs from the third or sixth arrangement example in the structure of the lens **40**. Let  $s_{15}(u'', t)$  be a signal representing the sum of signals on a line parallel to the  $v''$  direction. The arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{15}(u'', t)$  issued from the photodetector **46** and the arithmetic device structure for performing this processing are the same as the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_3(u'', t)$  or  $s_6(u'', t)$  obtained by the third or sixth arrangement example and the arithmetic device structure for performing this processing. Therefore, the arithmetic processing for obtaining the complex amplitude image  $g(\xi, \eta)$  according to  $s_{15}(u'', t)$  issued from the photodetector **46** and the arithmetic device structure for performing this processing will not be explained.

As illustrated in FIG. **45**, the arithmetic unit **50** in each of the first to fifteenth arrangement examples is constituted by a first Fourier transform device **51** which is an arithmetic device for performing a one-dimensional Fourier transform with respect to the time variable  $t$ , a specific region cutting device **55** which is an arithmetic device for cutting out data of a region including the range of a Nyquist frequency  $f_{nyq}$  about the difference frequency  $\Delta f$  acting as the center, a third Fourier transform device **53** which is an arithmetic device for performing a one-dimensional Fourier transform with respect to the temporal frequency, and a fourth Fourier transform device **54** which is an arithmetic device for performing a one-dimensional Fourier transform with respect to the first direction. The four kinds of arithmetic devices mentioned above will also be collectively referred to as basic arithmetic devices in the following in this specification.

In each of the first to fifteenth arrangement examples, photodetectors **46** and arithmetic units **50** are arranged in parallel in a direction (X direction) perpendicular to the sheet of FIG. **45**. In the photodetectors **46** and arithmetic units **50** arranged in parallel, FIG. **45** illustrates the photodetector **46** and arithmetic unit **50** at position  $u_n$ . Each of FIGS. **46** to **50**, **56**, **61**, and **62** in the following also illustrates one set of the photodetector **46** and arithmetic unit **50** at the position  $u_n$  among the photodetectors **46** and arithmetic units **50** arranged in parallel in a direction (X direction) perpendicular to the drawing sheet. The position  $u_n$  will also be written as  $u'_n$  and  $u''_n$  according to the arrangement examples.

#### Sixteenth Arrangement Example

The sixteenth arrangement example will now be explained. The sixteenth arrangement example differs from the first to fifteenth arrangement examples in that it includes a plurality of photodetectors **46** and a summing device (summing device) **58** for yielding the sum of outputs from the plurality of photodetectors **46**. Consequently, the sixteenth arrangement example differs from the first to fifteenth arrangement examples in the arrangement of the basic arithmetic devices.

The sixteenth arrangement example is constituted by one light source **10**, one lens **40**,  $M$  ( $M > 1$ ) photodetectors **46** (a plurality of detectors), and an arithmetic unit **50** including a plurality of basic arithmetic devices and a summing device **58**.

In the sixteenth arrangement example, the  $M$  photodetectors **46** are arranged in a row in the second direction. The  $m$ -th photodetector **46m** in the second direction outputs data representing the sum in the second direction at each position of the first direction at each time.

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The arithmetic unit **50** in the sixteenth arrangement example includes the summing device **58** that is an arithmetic device for receiving outputs of the M photodetectors arranged in a row in the second direction and issuing the sum of 1 to M. The summing device **58** may receive outputs of M basic arithmetic devices inputting outputs of the M photodetectors **46** arranged in a row in the second direction and issue the sum of 1 to M.

When located in front of the first Fourier transform device **51** as illustrated in FIG. **46**, the summing device **58** receives M signals issued from the M photodetectors. The summing device **58** also obtains the sum of 1 to M for the M signals at each time and outputs the result at each time.

When located between the first and third Fourier transform devices **51**, **53** as illustrated in FIGS. **47** and **48**, the summing device **58** receives M signals issued from the first Fourier transform device **51**. The summing device **58** also obtains the sum of 1 to M for the M signals at each temporal frequency and outputs the result at each temporal frequency.

When located behind the third Fourier transform device **53** as illustrated in FIGS. **49** and **50**, the summing device **58** receives M signals issued from the third Fourier transform device **53**. The summing device **58** also obtains the sum of 1 to M for the M signals at each time and outputs the result at each time.

The output of the summing device **58** will now be explained. When located between the first and third Fourier transform devices **51**, **53**, the summing device **58** obtains the sum of 1 to M according to the following expression (24) at each temporal frequency  $\omega (= \Delta\omega + \omega_d)$ . Here,  $S^{(m)}(u, \omega)$  represents the output signal of the first Fourier transform device **51** receiving output data  $s^{(m)}(u, t)$  of the m-th detector arranged in the second direction and Fourier-transforming them with respect to the time variable t. Due to the linearity of the Fourier transform, the Fourier transform operator  $FT_t$  in the middle of the expression (24) is exchangeable with the summation operator  $\Sigma$ , whereby the rightmost side of the expression (24) is obtained.

[Math. 24]

$$\sum_{m=1}^M S^{(m)}(u, \omega) = \sum_{m=1}^M FT_t [s^{(m)}(u, t)] \quad (24)$$

$$= FT_t \left[ \sum_{m=1}^M s^{(m)}(u, t) \right]$$

The term on which the one-dimensional Fourier transform operator  $FT_t$  with respect to the time variable t acts in the rightmost side represents the sum  $s(u, t)$  of 1 to M of the waveforms  $s^{(m)}(u, t)$  issued from the M photodetectors. That is, the summing device **58** provided in the arithmetic unit sends out the output of the first Fourier transform device **51** receiving the signals issued from any of the detectors in the first to fifteenth arrangement examples. Therefore, the sixteenth arrangement example can also be regarded as a structure in which a part of the detector outputting the sum of the signals in the second direction at each time is included in the arithmetic unit.

When located behind the third Fourier transform device **53**, on the other hand, the summing device **58** obtains the sum of 1 to M according to the following expression (25) at each time. Here,  $s^{(m)}(u, t)$  represents the output data of the third Fourier transform device **53m**. The output of the m-th detector arranged in the second direction is connected to the input of

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the third Fourier transform device **53m** through the first Fourier transform device **51m** and specific region cutting device **55m**. The one-dimensional Fourier transform of  $s^{(m)}(u, t)$  with respect to the time variable t is  $S^{(m)}(u, \omega_d)$ . The term on which the one-dimensional Fourier transform operator  $FT_{\omega}$  acts in the right side of the expression (25) represents output data of the specific region cutting device **55**. Therefore, the input of the specific region cutting device **55** is a signal  $S^{(m)}(u, \Delta\omega + \omega_d)$  whose frequency is shifted by the difference frequency  $\Delta\omega$  indicated in the left side of the expression (26). The rightmost side of the expression (26) represents the sum of 1 to M of the waveforms  $s^{(m)}(u, t)$  issued from the M photodetectors.

[Math. 25]

$$\sum_{m=1}^M s^{(m)}(u, t) = \sum_{m=1}^M FT_{\omega}^{-1} [S^{(m)}(u, \omega_d)] \quad (25)$$

[Math. 26]

$$\sum_{m=1}^M FT_{\omega}^{-1} [S^{(m)}(u, \Delta\omega + \omega_d)] = \sum_{m=1}^M s^{(m)}(u, t) \quad (26)$$

$$= s(u, t)$$

That is, the output of the summing device **58** provided in the arithmetic unit coincides with the signal issued from the detector in each of the first to fifteenth arrangement example, whereby the sixteenth arrangement example can be regarded as a structure in which a part of the detector outputting the sum of the signals in the second direction at each time is included in the arithmetic unit.

An example of the sixteenth arrangement example will now be explained. The lens **40** similar to that in the first arrangement example illustrated in FIG. **12** was used in the sixteenth arrangement example. That is, the light-receiving surface of the photodetector **46** was arranged on the back focal plane in the first direction of the lens **40**, which was also the back focal plane in the second direction of the lens **40**. As the photodetector **46**, a digital CCD camera equipped with two-dimensionally arranged 640×480 pixels, each having a pixel size of 8.3×8.3  $\mu\text{m}$ , was used. Its frame rate  $f_{CCD}$  was 30 Hz. Let m and n be the pixel numbers in the v and u directions, respectively. The photodetector **46** was arranged such that an object moved in a direction parallel to the v direction. Only a region having 312×312 pixels in the 640×480 pixels in total of the photodetector **46** was used for an experiment. Therefore,  $M=N=312$ . Here, M and N represent the numbers of pixels in the vertical and horizontal directions, respectively, while their lower-case letters m and n indicate their corresponding pixel numbers.

That is, the photodetector **46** in the sixteenth arrangement example is a photodetector in which M one-dimensional line sensors, each comprising N light-receiving pixels  $d_n^{(m)}$  arranged in the first direction, are arranged in the second direction. Let  $S^{(m)}(u, \omega)$  be the waveform obtained after Fourier-transforming the temporal waveform  $s^{(m)}(u, t)$  issued from each light-receiving pixel  $d_n^{(m)}$  with respect to the time variable t. FIG. **51** represent the temporal waveforms  $s^{(m)}(u, t)$ . FIG. **52** represents  $S^{(m)}(u, \omega)$ .

FIG. **53** is a chart illustrating a frequency having the maximum amplitude at each position (m, n) in the temporal frequency spectrum  $S^{(m)}(u, \omega)$  in pseudocolor display. In FIG. **53**, a) to e) are observation points of the waveforms represented in FIGS. **51** and **52**. FIG. **54** illustrates results of output



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at each temporal frequency from the summing device 58 having received the output  $S^{(m)}(u_1, \omega)$  on a line 1 (position  $u_1$ ) in the output of the first Fourier transform device 51 and yielded the sum of  $S^{(m)}(u_1, \omega)$  on the line 1 at each temporal frequency.

From the expression (24), the output of the summing device 58 corresponds to  $G(u, \Delta\omega + \omega_d)$  in the first arrangement example, so that the method of operating the data  $G(u, \Delta\omega + \omega_d)$  is the same as that in the first arrangement example. The upper side in FIG. 55 illustrates the amplitude image (upper left) and phase image (upper right) obtained when a frequency region including a range of a Nyquist frequency  $f_{nyq} = 5$  Hz in upper and lower region of  $\Delta f = 10$  Hz acting as the center frequency was cut out by the specific region cutting device 55. As a result, the complex amplitude image of the object 2 was obtained by arithmetic operations similar to those in the first arrangement example as illustrated in the lower side of FIG. 55.

As in the foregoing, the object 2 moving at the speed of 100  $\mu\text{m}/\text{sec}$  could be captured without blurring under the conditions where  $\Delta f = 10$  Hz,  $f_{CCD} = 30$  Hz, and Nyquist frequency  $f_{nyq} = 5$  Hz. One still image was obtained from 1000 interference images acquired within a capture time of about 33 seconds.

#### Seventeenth Arrangement Example

The seventeenth arrangement example has a structure including a plurality of photodetectors 46 and the summing device 58 as in the sixteenth arrangement example. That is, the seventeenth arrangement example is constituted by one light source 10, one lens 40,  $M$  ( $M > 1$ ) photodetectors 46, and an arithmetic unit 50 as with the sixteenth arrangement example. The arithmetic unit 50 includes a plurality of basic arithmetic devices and a summing device 58 for yielding the sum of outputs from the photodetectors 46. That is, the seventeenth arrangement example comprises a plurality of detectors, while the arithmetic unit 50 further comprises the summing device 58 for yielding the sum of outputs from the plurality of detectors.

When the lens 40 and the arithmetic unit 50 are regarded as an arithmetic unit, the lens 40 is incorporated in the arithmetic unit in the seventeenth arrangement example. The seventeenth arrangement example has a structure in which an arithmetic device for performing a Fourier transform or Fresnel transform with respect to the second direction (hereinafter referred to as second direction converter 59) is added to the arithmetic unit 50 of the first arrangement example. The second direction converter for performing the Fourier transform or Fresnel transform with respect to the second direction corresponds to the converter recited in the claims.

As illustrated in FIGS. 56, 61, and 62, the second direction converter 59 is arranged in front of the summing device 58 within the arithmetic unit 50 that receives outputs from the photodetectors 46. The second direction converter 59, regardless of its arithmetic operation position, receives  $M$  outputs at a position  $m$  ( $v_m, v'_m, v''_m$ ) and issues the result of the arithmetic operation.

When the second direction converter 59 is a Fourier transform unit, it is equivalent to the eighth arrangement example in which a Fraunhofer diffraction image and an object image are received on the light-receiving surface of the photodetector 46 in the first and second directions, respectively. That is, the lens 40 used in the first arrangement example and the second direction converter 59 constitute the lens 40 in the eighth arrangement example.

When the second direction converter 59 is a Fresnel transform unit, it is equivalent to the ninth arrangement example in which a Fraunhofer diffraction image and a Fresnel diffrac-

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tion image are received on the light-receiving surface of the photodetector 46 in the first and second directions, respectively. That is, the lens 40 used in the first arrangement example and the second direction converter 59 constitute the lens 40 in the ninth arrangement example.

#### Eighteenth Arrangement Example

The eighteenth arrangement example has a structure including a plurality of photodetectors 46 and the summing device 58 as in the sixteenth arrangement example. That is, the eighteenth arrangement example is constituted by one light source 10, one lens 40,  $M$  ( $M > 1$ ) photodetectors 46, and an arithmetic unit 50 including a plurality of basic arithmetic devices and the summing device 58 as with the sixteenth arrangement example. That is, the eighteenth arrangement example comprises a plurality of detectors, while the arithmetic unit 50 further comprises the summing device 58 for yielding the sum of outputs from the plurality of detectors.

When the lens 40 and the arithmetic unit 50 are regarded as an arithmetic unit, the lens 40 is incorporated in the arithmetic unit in the eighteenth arrangement example. The eighteenth arrangement example has a structure in which a second direction converter 59 for performing a Fourier transform or Fresnel transform with respect to the second direction (i.e., with respect to  $m$ ) is added to the arithmetic unit 50 of the second arrangement example.

As illustrated in FIGS. 56, 61, and 62, the second direction converter 59 is arranged in front of the summing device 58 within the arithmetic unit 50 that receives outputs from the photodetectors. The second direction converter 59, regardless of its arithmetic operation position, receives  $M$  outputs at a position  $m$  ( $v_m, v'_m, v''_m$ ) and issues the result of the arithmetic operation.

When the second direction converter 59 is a Fourier transform unit, it is equivalent to the tenth arrangement example in which an object image and a Fraunhofer diffraction image are received on the light-receiving surface of the photodetector 46 in the first and second directions, respectively. That is, the lens 40 used in the second arrangement example and the second direction converter 59 constitute the lens 40 in the tenth arrangement example.

When the second direction converter 59 is a Fresnel transform unit, it is equivalent to the twelfth arrangement example in which an object image and a Fresnel diffraction image are received on the light-receiving surface of the photodetector 46 in the first and second directions, respectively. That is, the lens 40 used in the second arrangement example and the second direction converter 59 constitute the lens 40 in the twelfth arrangement example.

An example of the eighteenth arrangement example will now be explained. The lens 40 similar to that in the second arrangement example illustrated in FIG. 22 was used in the eighteenth arrangement example. That is, the light-receiving surface of the photodetector 46 was arranged such that an object image was formed on the light-receiving surface of the photodetector 46 in each of the first and second directions. The second direction converter 59 received outputs from the  $M$  photodetectors at each time and fed the results of arithmetic operations to the summing device 58. FIG. 56 illustrates a block diagram of this example.

As the photodetector 46, a digital CCD camera equipped with two-dimensionally arrayed  $640 \times 480$  pixels, each having a pixel size of  $8.3 \times 8.3 \mu\text{m}$ , was used. Its frame rate  $f_{CCD}$  was 30 Hz. Let  $m$  and  $n$  be the pixel numbers in the  $v'$  and  $u'$  directions, respectively. The photodetector 46 was arranged such that an object moved in a direction parallel to the  $v'$  direction. Only a region having  $312 \times 312$  pixels in the  $640 \times 480$  pixels in total of the photodetector 46 was used for an

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experiment. Therefore,  $M=N=312$ . Here,  $M$  and  $N$  represent the numbers of pixels in the vertical and horizontal directions, respectively, while their lower-case letters  $m$  and  $n$  indicate their corresponding pixel numbers.

In the eighteenth arrangement example, the sample illustrated in FIG. 24 was measured as the object 2. FIG. 57 illustrates  $M$  pieces of input data at the position  $u'$  fed to the second direction converter 59 at each time (numbers 1 to 10 in the diagram corresponding to times). The second direction converter 59 performed a Fourier transform.

The waveform  $\text{Re}[\text{FT}_m[s^{(m)}(u', t)]]$  issued from the second direction converter 59 is sent to the summing device 58, where the sum is taken with respect to  $m$ , so as to yield  $s(u', t)$ .  $\text{FT}_m$  represents a one-dimensional Fourier transform with respect to the variable  $m$ .  $\text{Re}$  is an operator for taking a real part of a complex number. Since the lens 40 used in the second arrangement example and the second direction converter 59 construct the lens 40 in the tenth arrangement example, the data issued from the summing device 58 are the same as the signals issued from the detectors in the tenth arrangement example. Since the tenth arrangement example has been explained as one in which the signals issued from its detectors are operated in the same method as in the second arrangement example, the eighteenth arrangement example yields the complex amplitude image  $g(\xi, \eta)$  by the arithmetic operation method of the second arrangement example.

FIG. 57 illustrates input images of the second direction converter 59 in the eighteenth arrangement example. FIG. 58 represents  $M$  pieces of output data at the position  $u'$  issued from the second direction converter 59 at each time. The upper part of FIG. 59 illustrates data issued at each time from the summing device 58 having acquired the sum of 1 to  $M$  at each time. The middle part of FIG. 59 illustrates the amplitude image in the output one-dimensionally Fourier-transformed with respect to the time variable  $t$  by the first Fourier transform device 51. The lower side of FIG. 59 illustrates the phase image in the output one-dimensionally Fourier-transformed with respect to the time variable  $t$  by the first Fourier transform device 51.

The upper part of FIG. 60 illustrates results of outputs from the specific region cutting device, with its left and right sides representing the amplitude image and phase image, respectively. The lower side of FIG. 60 illustrates results of a one-dimensional Fourier transform with respect to the temporal frequency by the third Fourier transform device 53, with its left and right sides representing the amplitude image and phase image, respectively.

#### Nineteenth Arrangement Example

The nineteenth arrangement example has a structure including a plurality of photodetectors 46 and the summing device 58 as in the sixteenth arrangement example. That is, the nineteenth arrangement example is constituted by one light source 10, one lens 40,  $M$  ( $M>1$ ) photodetectors 46, and an arithmetic unit 50 including a plurality of basic arithmetic devices and the summing device 58 as with the sixteenth arrangement example. That is, the nineteenth arrangement example comprises a plurality of detectors, while the arithmetic unit 50 further comprises the summing device 58 for yielding the sum of outputs from the plurality of detectors.

When the lens 40 and the arithmetic unit 50 are regarded as an arithmetic unit, the lens 40 is incorporated in the arithmetic unit 50 in the nineteenth arrangement example. The nineteenth arrangement example has a structure in which a second direction converter 59 for performing a Fourier transform or Fresnel transform with respect to the second direction (i.e., with respect to  $m$ ) is added to the arithmetic unit 50 of the third arrangement example.

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As illustrated in FIGS. 56, 61, and 62, the arithmetic operation position of the second direction converter 59 is arranged in front of the summing device 58 within the arithmetic unit that receives outputs from the detectors. The second direction converter 59, regardless of its arithmetic operation position, receives  $M$  outputs at a position  $m$  ( $v_m, v'_m, v''_m$ ) and issues the result of the arithmetic operation.

When the second direction converter 59 is a Fourier transform unit, it is equivalent to the fifteenth arrangement example in which Fresnel diffraction images are received on the light-receiving surface of the photodetector 46 in the first and second directions. That is, the lens 40 used in the third arrangement example and the second direction converter 59 constitute the lens 40 in the fifteenth arrangement example.

When the second direction converter 59 is a Fresnel transform unit, it is equivalent to the fifteenth arrangement example in which Fresnel diffraction images are received on the light-receiving surface of the photodetector 46 in the first and second directions. That is, the lens 40 used in the third arrangement example and the second direction converter 59 constitute the lens 40 in the fifteenth arrangement example.

The arithmetic operation position of the second direction converter 59 where the outputs from the photodetectors 46 are received in the arithmetic unit 50 will now be explained. It is the position of the lens 40 when the second direction converter 59 is included in the lens 40. When not included in the lens 40, the second direction converter 59 is arranged in front of the summing device 58 receiving outputs from the photodetectors 46 within the arithmetic unit 50.

When the second direction converter 59 is located between the detector and the first Fourier transform device 51, the input of the second direction converter 59 receives outputs from the  $M$  photodetectors at each time and issues the result of arithmetic operations at each time.

When the second direction converter 59 is located between the first and third Fourier transform devices 51, 53, the input of the second direction converter 59 receives outputs from the  $M$  photodetectors at each temporal frequency and issues the result of arithmetic operations at each temporal frequency.

When the second direction converter 59 is located behind the third Fourier transform device 53, the input of the second direction converter 59 receives outputs from the  $M$  photodetectors at each time and issues the result of arithmetic operations at each time.

#### Twentieth Arrangement Example

The twentieth arrangement example will now be explained. In the first to nineteenth arrangement examples, a method described in Literature 1 (Gabriel Popescu, "Fourier phase microscopy for investigation of biological structures and dynamics," Optics letters, 29, 2503, (2004)) was used for separating zero-order light and higher-order light (non-Doppler-shifted light and Doppler-shifted light) in the object light (scattered light from the object). That is, the lens 40 is arranged between the object 2 and the light-receiving surface of the photodetector 46. The lens 40 temporarily forms a Fraunhofer diffraction image between the object 2 and the light-receiving surface of the photodetector 46. The substantially zero-order light concentrating in the vicinity of the center of the Fraunhofer diffraction image is employed as the reference light.

The twentieth arrangement example uses the diffraction grating described in Literature 2 (Gabriel Popescu, "Diffraction phase microscopy for quantifying cell structure and dynamics," Optics letters, 31, 775, (2006)) as a method for extracting the substantially zero-order light. FIG. 63 illustrates a specific optical system therefor.

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As illustrated in FIG. 63, the lens 40 is arranged between the object 2 and the light-receiving surface of the photodetector 46. The lens 40 temporarily forms a Fraunhofer diffraction image subsequent to the object image between the object 2 and the light-receiving surface of the photodetector 46. The lens 40 in the twentieth arrangement example is constituted by the lens 40 in the second arrangement example and lenses 407, 408 for relaying the object image formed by the lens 40. The lenses 407, 408 construct a 4f optical system. The lens 40 in the twentieth arrangement example is constituted by four spherical lenses.

Constructing the lens 40 as mentioned above forms an object image of the object 2 between the lenses 404, 407, and a Fraunhofer diffraction image of the object 2 between the lenses 407, 408. The planes where the object image and Fraunhofer diffraction image are formed will be referred to as object image plane and Fraunhofer diffraction image plane, respectively.

A diffraction grating and the beam splitter 12 are arranged on the object image plane and Fraunhofer diffraction image plane, respectively. The diffraction grating forms a plurality of Fraunhofer diffraction images on the Fraunhofer diffraction image plane. Among them, the zero-order and +first-order diffraction images will be referred to as the zero-order diffraction image and first-order diffraction image, respectively. The direction of grooves of the diffraction grating coincides with the X direction. Therefore, the zero-order and +first-order diffraction images are arranged like a line perpendicular to the Y direction by the diffraction grating.

A pinhole 63 comprises two holes formed so as to cover therein the substantially zero-order light in the zero-order diffraction image and the first-order diffraction image, which are produced by the diffraction grating, respectively. In the zero-order diffraction image, the light transmitted through the hole (pinhole 63A) opened so as to cover the substantially zero-order light therein becomes the second light, which is fed to the first modulator through the beam splitter 12 and lens 60. The light transmitted through the hole (pinhole 63A) opened so as to cover the substantially zero-order light therein becomes the second light, which is fed to the first modulator by way of the beam splitter 12 and lens 60. The light transmitted through the hole (pinhole 63B) opened so as to cover the first-order diffraction image therein becomes the first light, which is fed to the lens 408. That is, the diffraction grating and pinholes 63A, 63B, which separate the first light and second light from each other, act like the beam splitter 12 in the first to nineteenth arrangement examples.

The beam splitter 12 in the twentieth arrangement example may be a mirror which reflects light without transmitting it therethrough. The beam splitter 12 feeds the lens 60 with the light transmitted through the hole (pinhole 63A) opened so as to cover the substantially zero-order light in the pinhole 63. The front focal plane of the lens 60 is on the same plane as the pinhole 63, while the front focal point of the lens 60 coincides with the center of the pinhole 63A. The foregoing structure can extract the substantially zero-order light as the reference light in the twentieth arrangement example as in the first to nineteenth arrangement examples.

When the speed of the object 2 changes, a frequency modulation occurs in the Doppler signal, whereby the finally obtained image of the object 2 elongates or shortens in the flow direction in the observation device 1 of this embodiment. Preferably, for correcting such elongation or shortening, the observation device 1 of this embodiment further comprises a speed detector for detecting the moving speed of the object 2. Preferably, the arithmetic unit 50 performs a correction for the change in speed of the object 2 according to the speed of

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the object 2 detected by the speed detector when a one-dimensional or two-dimensional Fourier transform with respect to a time variable. The sampling interval of the signals issued from the photodetector 46 may be based on the speed of the object 2 detected by the speed detector.

The speed detector, for which a given one is usable, can also determine the moving speed of the object 2 by detecting the frequency of the signal at the position where the scattered light reaches the back focal plane of the lens 40 according to the relationship between the moving speed and the Doppler shift frequency. In this case, the speed detector may detect a split part of the light directed from the beam splitter 41 to the photodetector 46 on the Fourier plane or include a pixel independently provided in a part of the light-receiving surface of the photodetector 46. Preferably, the pixel has such an area as to exhibit a resolution of the moving speed derived from the relationship between the moving speed  $V$  of the object 2 and the Doppler frequency  $f_d$ .

In the first arrangement example in the observation device 1 of this embodiment, the light (zero-order light) not scattered by the object 2 in the light  $L_0$  irradiating the object 2 is converged at one point by the lens 40. For preventing such zero-order light from wholly reaching the light-receiving surface of the photodetector 46, the neutral density filter 45 for attenuating the zero-order light is preferably provided. It is also preferred for the object 2 to be irradiated with the light  $L_0$  having such a beam cross section that the zero-order light occurs less. Preferably, the optical intensity reaching the photodetector 46 when no object 2 exists between the light source 10 and the photodetector 46 is taken into account into correcting the intensity distribution  $A_0$ .

The foregoing explains a case where the object 2 moves in one direction on the  $\xi\eta$  plane. The present invention is also applicable to a case where the object 2 moves back and forth in the  $\zeta$  direction (direction of the optical axis of the lens 40) perpendicular to the  $\xi\eta$  plane. In this case, a Doppler shift occurs radially on the back focal plane of the lens, whereby a photodetector having a circular pixel array structure in which each pixel extends radially is used.

Though the foregoing explanation mainly represents examples in which the phase image of the object is acquired by transmitted illumination, it can also be acquired by reflected illumination as a matter of course. While light in the single longitudinal mode is preferably utilized as the light source for detecting the Doppler shift frequency with high sensitivity, it is not restrictive. For example, using broadband light can also acquire information concerning the depth of phase objects. For measuring the Doppler shift frequency of each wavelength component, light having a fixed phase relationship between wavelength components is preferably used as the wideband light. As such a light source, a mode-locked laser can be used, for example. The mode-locked laser has discrete wavelength components and thus is a very effective light source for detecting the Doppler shift frequency.

#### Industrial Applicability

Recently, using the term "label-free" as a keyword, attention has been directed to a technique for visualizing cells as the object 2 without staining, so as to discriminate them and so forth. This technique is applied to the observation and diagnosis of cells (cytodiagnosis) for the purpose of retaining cells cultured in vitro to an in vivo state, such as regenerative medicine. On the other hand, circulating tumor cells (CTC), which have recently been attracting attention, are contained in normal nucleated blood cells (i.e., leukocytes) at a rate of about one per 10 million, so that tests must be done rapidly in order to enhance their detectability. The present invention is applicable to such a field. The present invention is also appli-

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cable to flow cytometry yielding high throughput. The present invention can observe the moving object 2 by using a one-dimensional photodetector as the photodetector 46, so as to improve the frame rate, and let the object 2 such as cells to flow at high speed, thereby increasing the throughput in testing. Cell specimens and tissue specimens attached to glass slides can also be imaged with favorable contrast without staining. Complex amplitude images can also be obtained under reflected light as in metallographic microscopes.

## Reference Signs List

1 . . . observation device; 2 . . . object; 10 . . . light source; 11 . . . illumination lens; 12 . . . beam splitter; 20 . . . first modulator; 21 . . . first signal generator; 22 . . . first amplifier; 30 . . . second modulator; 31 . . . second signal generator; 32 . . . second amplifier; 40 . . . lens; 41 . . . beam splitter; 42, 43 . . . mirror; 44 . . . lens; 45 . . . neutral density filter; 46 . . . photodetector; 50 . . . arithmetic unit; 51 . . . first Fourier transform device; 52 . . . second Fourier transform unit; 53 . . . third Fourier transform device; 54 . . . fourth Fourier transform device; 55 . . . specific region cutting device; 56 . . . initial phase correction device; 57 . . . quadratic phase dividing device; 58 . . . summing device; 59 . . . second direction converter; 60 . . . quadratic phase correction unit

The invention claimed is:

1. A phase image acquisition device comprising:
  - a light source configured to emit light to irradiate a moving object;
  - a first optical system configured to split the emitted light in two behind the object so as to yield first light and second light, and modulate the second light with a modulator;
  - a second optical system configured to cause a heterodyne interference between the first light and the modulated second light;
  - a detection unit comprising a light-receiving surface that has pixels arrayed in a first direction and configured to receive light being heterodyne interfered on the light-receiving surface, and output data representing a sum in a second direction of light having reached each pixel on the light-receiving surface, at each position in the first direction at each time, wherein the first direction is a direction on the light-receiving surface yielding a fixed Doppler shift effect caused by a movement of the object and perpendicular to a moving direction of the object, and the second direction is a direction orthogonal to the first direction and parallel to the moving direction of the object; and
  - an arithmetic unit comprising a calculator and configured to perform a one-dimensional Fourier transform of data employing the position in the first direction on the light-receiving surface and time as variables with respect to a time variable and a two-dimensional Fourier transform of the Fourier-transformed data, so as to yield data obtained by the two-dimensional Fourier transform as an image of the object.
2. The phase image acquisition device according to claim 1, wherein the arithmetic unit comprises:
  - a first Fourier transform device configured to perform the one-dimensional Fourier transform with respect to the time variable; and
  - a second Fourier transform unit configured to perform the two-dimensional Fourier transform; and
 wherein the second Fourier transform unit comprises a third Fourier transform device configured to perform a one-dimensional Fourier transform with respect to a frequency and a fourth Fourier transform device configured to perform a one-dimensional Fourier transform with respect to the first direction.

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3. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a back focal plane in the first direction of the lens, while serving as a back focal plane in the second direction of the lens; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

4. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fraunhofer diffraction image of the object is formed by the lens in the first direction, while serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

5. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fraunhofer diffraction image of the object is formed by the lens in the first direction, while serving as a plane where an image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

6. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fraunhofer diffraction image of the object is formed by the lens in the first direction, while serving as a plane where a Fresnel diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

7. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction;

wherein the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

8. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

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wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where an image of the object is formed in the second direction;

wherein the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

9. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where a Fresnel diffraction image of the object is formed in the second direction;

wherein the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

10. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction, while serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, fourth Fourier transform device, and fourth Fourier transform device are arranged in sequence.

11. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction, while serving as a plane where an image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, fourth Fourier transform device, and fourth Fourier transform device are arranged in sequence.

12. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

wherein the light-receiving surface of the detection unit is arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction, while serving as a plane where a Fresnel diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, third Fourier transform device, fourth Fourier transform device, and fourth Fourier transform device are arranged in sequence.

13. The phase image acquisition device according to claim 2, further comprising a lens arranged between the light source and the detection unit;

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wherein the light-receiving surface of the detection unit is arranged on a plane where a Fresnel diffraction image of the object is formed by the lens in the first direction, while serving as a plane where a Fresnel diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, fourth Fourier transform device, third Fourier transform device, and fourth Fourier transform device are arranged in sequence.

14. The phase image acquisition device according to claim 1, wherein the arithmetic unit performs the two-dimensional Fourier transform of data in a region including a range of a Nyquist frequency in upper and lower region of a difference frequency between first and second modulation frequencies in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

15. A phase image acquisition device comprising:

a light source configured to emit light to irradiate a moving object;

a first optical system configured to split the emitted light in two behind the object so as to yield first light and second light, and modulate the second light with a modulator;

a second optical system configured to cause a heterodyne interference between the first light and the modulated second light;

a detection unit comprising a light-receiving surface that has pixels arrayed in a first direction and configured to receive light being heterodyne interfered on the light-receiving surface, and output data representing a sum in a second direction of light having reached each pixel on the light-receiving surface, at each position in the first direction at each time, wherein the first direction is a direction on the light-receiving surface yielding a fixed Doppler shift effect caused by a movement of the object and perpendicular to a moving direction of the object, and the second direction is a direction orthogonal to the first direction and parallel to the moving direction of the object;

an arithmetic unit comprising a calculator and configured to perform, for data employing a position in the first direction on the light-receiving surface and time as variables, a one-dimensional Fourier transform with respect to a time variable, a one-dimensional Fourier transform with respect to the frequency, and a one-dimensional Fourier transform with respect to the first direction, so as to yield data obtained by the one-dimensional Fourier transforms as an image of the object.

16. The phase image acquisition device according to claim 15, further comprising a lens arranged between the light source and the detection unit;

wherein the arithmetic unit comprises a first Fourier transform device configured to perform the one-dimensional Fourier transform with respect to the time variable and a third Fourier transform device configured to perform the one-dimensional Fourier transform with respect to a frequency,

wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where an image of the object is formed in the second direction;

wherein the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

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17. The phase image acquisition device according to claim 15, further comprising a lens arranged between the light source and the detection unit;

wherein the arithmetic unit comprises a first Fourier transform device configured to perform the one-dimensional Fourier transform with respect to the time variable and a third Fourier transform device configured to perform the one-dimensional Fourier transform with respect to a frequency;

wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where a Fraunhofer diffraction image of the object is formed in the second direction;

wherein the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

18. The phase image acquisition device according to claim 15, further comprising a lens arranged between the light source and the detection unit;

wherein the arithmetic unit comprises a first Fourier transform device configured to perform the one-dimensional Fourier transform with respect to the time variable and a third Fourier transform device configured to perform the one-dimensional Fourier transform with respect to a frequency;

wherein the light-receiving surface of the detection unit is arranged on a plane where an image of the object is formed by the lens in the first direction, while serving as a plane where a Fresnel diffraction image of the object is formed in the second direction; and

wherein the light source, lens, detection unit, first Fourier transform device, and third Fourier transform device are arranged in sequence; and

wherein the lens performs the one-dimensional Fourier transform with respect to the first direction.

19. The phase image acquisition device according to claim 15, wherein the arithmetic unit further comprises an initial phase correction device configured to correct an initial phase included in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

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20. The phase image acquisition device according to claim 15, wherein the detection unit comprises a plurality of photodetectors; and

wherein the arithmetic unit further comprises an output summing amplifier configured to yield a sum of outputs from the plurality of photodetectors.

21. The phase image acquisition device according to claim 15, wherein the arithmetic unit further comprises a converter configured to perform a Fourier transform or Fresnel transform with respect to the second direction.

22. The phase image acquisition device according to claim 15, wherein the arithmetic unit performs the one-dimensional Fourier transform with respect to the frequency and the one-dimensional Fourier transform with respect to the first direction of data in a region including a range of a Nyquist frequency in upper and lower region of a difference frequency between first and second modulation frequencies in the data obtained by the one-dimensional Fourier transform with respect to the time variable.

23. The phase image acquisition device according to claim 15, further comprising a speed detector configured to detect a moving speed of the object;

wherein, during the one-dimensional Fourier transform with respect to the time variable, the arithmetic unit corrects a change in the speed of the object according to the moving speed.

24. The phase image acquisition device according to claim 15, wherein the irradiation of the object with the light is performed in an optical arrangement of transmitted illumination.

25. The phase image acquisition device according to claim 15, wherein the irradiation of the object with the light is performed in an optical arrangement of reflected illumination.

26. The phase image acquisition device according to claim 15, wherein the light source generates light in a single longitudinal mode.

27. The phase image acquisition device according to claim 15, wherein the light source generates wideband light.

28. The phase image acquisition device according to claim 27, wherein the light source generates a mode-locked laser.

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